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Advancements in hybrid photovoltaic systems for enhanced solar cells performance

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ABSTRACT

Photovoltaic (PV) cells can absorb up to 80% of the incident solar radiation available in the solar spectrum, however, only a certain percentage of the absorbed incident energy is converted into electricity depending on the conversion efficiency of the PV cell technology. The remainder of the energy is dissipated as heat accumulating on the surface of the cells causing elevated temperatures. Temperature rise of PV cells is considered as one of the most critical issues influencing their performance, causing serious degradation and shortening the life-time of the cells. Hence cooling of PV modules during operation is essential and must be an integral part of PV systems particularly in sun-drenched locations. Many researches have been conducted investigating a range of methods that can be employed to provide thermal management for PV systems. Among these designs, systems utilizing air, liquid, heat pipes, phase change materials (PCMs), and thermoelectric (TE) devices to aid cooling of PV cells. This paper provides a comprehensive review of various methods reported in the literature and discusses various design and operating parameters influencing the cooling capacity for PV systems leading to an enhanced performance.

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Contents

Abbreviations: a-Si, amorphous silicon; BIPV, building integrated photovoltaic; CPC-PVT, compound parabolic concentrating photovoltaic–thermal; CPV, concentrated photovoltaic; c-Si, crystalline silicon; FP-PVT, flat plate photovoltaic–thermal; HTS, high temperature stage; MCPVT, micro-channel photovoltaic–thermal; MCSCT, micro-channel solar cell-thermal; MEPCM, microencapsulated phase change material; PCM, phase change material; PV, photovoltaic; PV/e, photovoltaic/evaporator; PVT, photovoltaic–thermal; SAHP, solar assisted heat pump; STC, standard testing condition; TE, thermoelectric; TEC, thermoelectric cooler; TEG, thermoelectric generator

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Nomenclature

β	temperature coefficient
ΔT	temperature difference
FF	fill factor
I	current
I_{sc}	short-circuit current
η	efficiency
P	power
T	temperature
V	voltage
V_{oc}	open-circuit voltage

1. Introduction

Solar energy is one of the most widely adopted renewable energy source that can be utilized in various applications such as, thermal management using thermal collectors or electricity generation through special optical solar cells, also known as Photovoltaic (PV) cells. PV cells are semiconductor devices that have the ability to convert the energy available in both dispersed and concentrated solar radiation into direct current (DC) electricity [1–6]. Conversion of solar energy into electricity through PV cells is achieved at different efficiency ratings varying between 7 and 40% and determined primarily by the type of semiconductor material from which the cells are manufactured [2,3]. PV technology has been adopted in many regions world-wide as solar energy is ubiquitous and abundant on the earth's surface. PV systems offer wide range of applications from direct power supply for appliances to large power stations feeding electricity into the grid and serving large communities. Although PV systems have been commercially available and widely operated for many years, certain barriers stand towards widespread application of this particular technology. Issues such as limited conversion efficiency, elevated temperatures, and dust accumulation are considered critical due to their significant impact on the performance of PV cells especially in sun-drenched hot climate regions. Wide range of cooling techniques for thermal regulation of PV systems has been investigated. Among the proposed systems, air and liquid based cooling of PV systems are considered mature technologies and have been practically tested widely. On the contrary, the utilization of heat pipe, phase change materials, and thermoelectric devices to aid cooling of PV cells still remain at the research and development stage. Although various techniques have been investigated, practical solutions have not been identified for wide implementation in large scale projects. The issue of elevated temperatures on the performance of PV systems and the research conducted to tackle this matter is addressed in this paper.

2. Temperature influence on photovoltaic cells

PV cells absorb up to 80% of the incident solar radiation, however, only small part of the absorbed incident energy is converted into electricity depending on the conversion efficiency of the PV cell technology used [4]. The remainder energy is dissipated as heat and the PV module can reach temperatures as high as 40 °C above ambient. This is due the fact that PV cells convert a certain wavelength of the incoming irradiation that contributes to the direct conversion of light into electricity, while the rest is dissipated as heat [6]. The photoelectric conversion efficiency of commercially available single junction solar cells ranges between 6 and 25% under optimum operating conditions depending on the semiconductor material from which the cell is made [3,5]. However, PV systems do not operate under standard conditions, thus variation of operating temperatures limit the efficiency of PV systems. Such limited efficiency is associated with the band-gap energy of the semiconductor material [1,6]. Crystalline silicon PV cells can utilize the entire visible spectrum plus some part of the infrared spectrum. Nonetheless, the energy of the infrared spectrum, as well as the longer wavelength radiation are not sufficient to excite electrons in the semiconductor material to cause current flow [6]. On contrary, higher energy radiation is capable of producing current flow; however, much of this energy is similarly unusable. Consequently, radiations with high and low energies are not usable by the PV cell for electricity generation, and instead are dissipated at the cell as thermal energy.

Various elements affect the performance of PV modules in outdoor applications. Factors such as low irradiance, soiling, and high operating temperatures contribute towards dramatic degradations in the conversion efficiency and the technical life-time of the solar cells [7,8]. PV cells however tend to be affected mostly by high operating temperatures due to irradiance from the sun, especially concentrated radiation which tends to further elevate the temperature of the PV junction. The PV cell performance decreases with increasing temperatures, fundamentally owing to increased intrinsic carrier concentrations which tend to increase the dark saturation current of the p–n junction [6,9]. Reduction in band-gap due to high doping also serves to increase the intrinsic carrier concentration [6]. The increase in dark saturation current causes the open-circuit voltage to decrease linearly which for silicon at 300 K corresponds to about −2.3 mV/°C [6]. Huang et al. [10] performed experimental investigation to observe the variation of open-circuit voltage with temperature

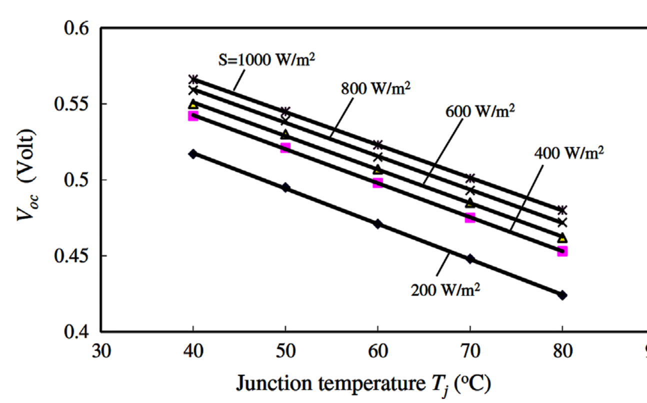

Fig. 1. Variation of open-circuit voltage with junction temperature of PV cell [10].

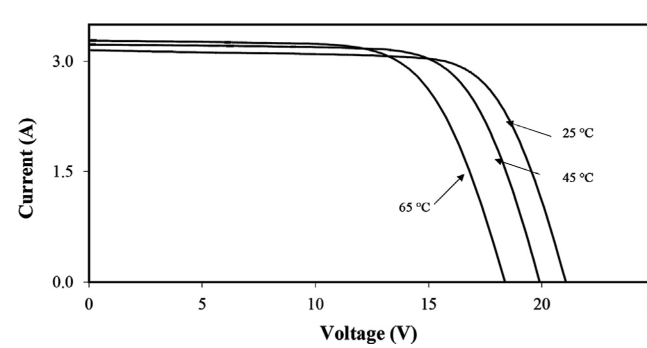

Fig. 2. Influence of temperature on PV module I–V curve [9].

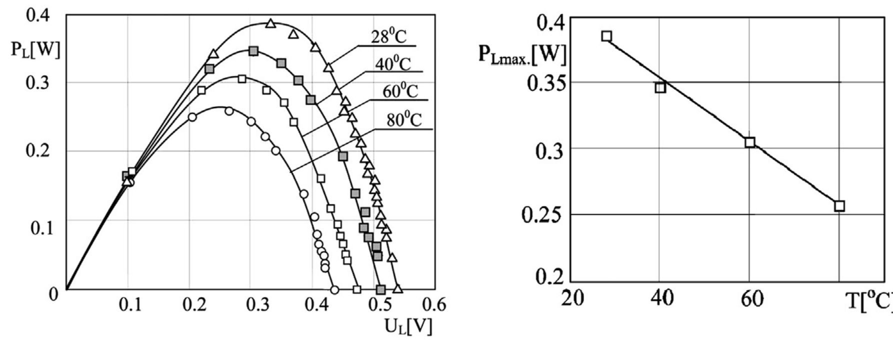

Fig. 3. Output power of single-crystalline silicon PV cells under different operating temperatures (left) temperature dependence of the maximum output power (right) [5].

Table 1
Temperature coefficients of different PV cell technologies.

T_{ref} (°C)	ηT_{ref} (%)	β_{ref} (°C^{-1})	PV technology	Refs.
25	16–24	0.0041	Mono-cSi	[17]
25	14–18	0.004	Poly-cSi	[18]
25	4–10	0.011	a-Si	[18]
25	7–12	0.0048	CIS	[14]
25	10–11	0.00035	CdTe	[14]

(40–80 °C) for various irradiance levels (200–1000 W/m^2), Fig. 1. The short-circuit current however, increases slightly due to decline in the band-gap energy, Fig. 2. Andreev et al. [11] estimated an increase in the short circuit current of 0.1%/°C due to reduction in the band-gap of the solar cell with temperatures varying between 20 and 100 °C. In spite of this increase in current, the degradation of the open-circuit voltage leads to a noticeable decrease in the available maximum electrical power which can be better observed through the characteristic curves of PV modules at different operating temperature in Fig. 3. For crystalline silicon PV cells, a drop in the electrical power output of about 0.2–0.5% was reported for every 1 °C rise in the PV module temperature principally due to the temperature dependence of the open-circuit voltage of the cell depending on the PV technology [5,12,13]. Such property of PV cells is known as the Temperature Coefficient of the PV cell. According to Del Cueto [14], the reduction in efficiency due to temperature dependence is in the range of absolute 1–2% over a temperature span of 30 °C. Table 1 presents the temperature coefficients of various PV technologies along with their typical efficiencies [15,16].

In addition, for a given power output of a PV module where a number of cells are electrically connected in series, the output voltage increases while the current decreases due to series connection, hence reducing Ohmic losses [19]. Nonetheless, the cell producing the least output in series string of cells limits the current; this is known as current matching issue [20]. Because the cell efficiency decreases with increasing temperature, the cell having the highest temperature will limit the efficiency of the entire string. Consequently, maintaining a homogeneous low temperature distribution across the string of cells is essential for an optimum performance of PV systems.

3. Cooling of photovoltaic (PV) cells

Due to the aforementioned temperature influence on the performance of PV cells, the energy that is not converted into electricity by the PV cells must be extracted to prevent excessive cell heating and the caused deteriorated performance. Therefore, solar cell cooling must be an integral part of PV systems, especially in concentrated PV designs in order to minimize the effect of elevated temperatures on the PV module power output. Furthermore, with the current state of incentives and the decreasing prices of solar modules, PV system prices are decreasing almost yearly and industries are primarily concerned with ensuring maximum system output (kW h/kWp) and prolonged PV system lifetime, since the longer the lifetime, the longer the energy output from the installed system [8]. Hence, the cost, referred to as (£/kW h) of the total kW h generated from a system on an annual basis can be lowered as PV system would experience less losses. In addition, with primary interest of improving systems' overall performance, extensive efforts have been devoted to look into mechanisms for waste heat recovery to compensate for the low array electrical efficiency.

Various methods can be employed to achieve cooling of PV systems. However, the optimum cooling solution is critically dependent on several factors such as, PV technology employed, types of concentrators' geometries, and weather conditions at which the system is installed. Challenges are mainly present in hot and humid climate regions where cells may experience both short and long term degradation due to excessive temperatures. Methods of cooling PV panels fall mainly into two categories, namely passive and active cooling.

Passive cooling mechanisms refer to technologies used to extract and/or minimize heat absorption from/of the PV panel without additional power consumption. The mechanism implies transporting heat from where it is generated and dissipating it to the environment [21]. Wide varieties of passive cooling options are available, simplest forms involve application of solids of high thermal conductivity metals, such as aluminum and copper, or an array of fins or other extruded surfaces to enhance heat transfer to the ambient [22]. More complex systems involve the use of phase change materials (PCMs) and various methods for natural circulation, in addition to the use of heat pipes that are able to transfer heat efficiently through a boiling–condensing process [21]. However, in such cooling systems heat dissipation is limited by the contact point between the heat-sink and the ambient, where the convective heat transfer coefficient and lesser the radiative heat transfer are limiting factors [20]. An example illustrating passive cooling of PV panels can be an array of PV panels installed on a roof of a house with heat-sinks attached at the back surface, in a way that allows air to naturally flow behind the panels, and extracts away heat through air convection, or the use of white-colored roof that prevents the surfaces around the panels from heating up and causing additional heat gain. However, with passive cooling the main heat transfer mechanism for a PV system on a windless day are through radiation and free convection, and both mechanism of the same low order of magnitude, therefore, the need for a cooling system that can actively dissipate heat can be essential especially in hot climate regions.

On the other hand, active cooling systems comprise of heat extraction utilizing devices such as fans to force air or pump water

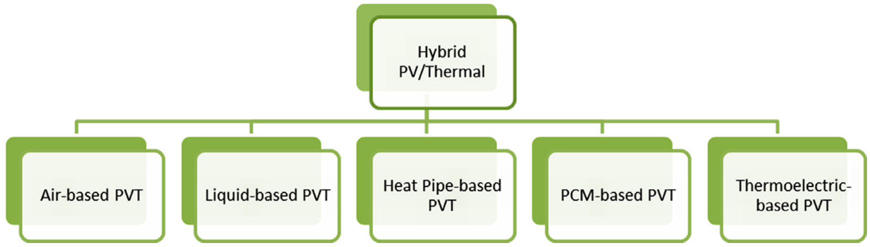

Fig. 4. Classification of PVT modules based on heat extraction mechanism.

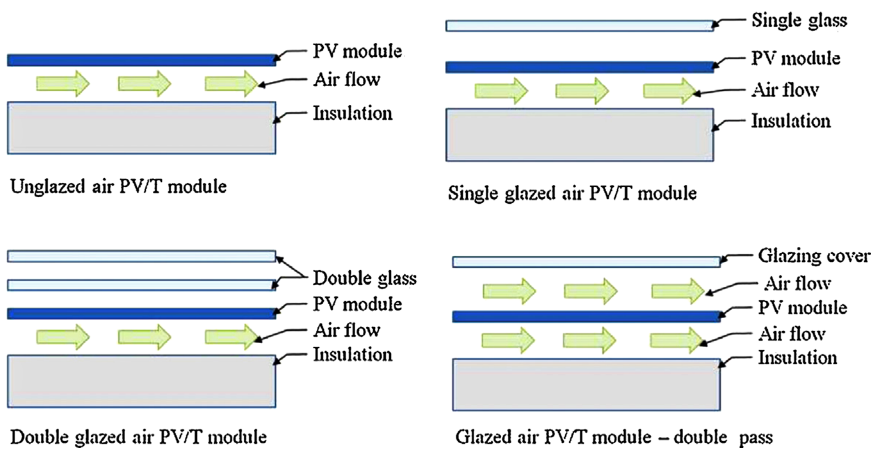

Fig. 5. Different designs of air-based PVT collectors [18].

to the panels to extract away the heat [20]. These systems are powered using energy to affect some kind of heat transfer usually by convection and conduction. Although an active system consumes power, they are commonly used in situations where the added efficiency to the panels is greater than the energy demanded to power the system, examples include solar power plants in deserts. These systems may also be used in situations where some additional benefit can be achieved, such as waste heat recovery for domestic water heating.

For both passive and active cooling systems the commonly used cooling mediums are air and water. However, the thermal properties of air make it less efficient as a coolant medium [19]. Therefore, air cooling is not well suited to the extraction of thermal energy from the PV absorber at hot regions. This implies that more parasitic power to operate fans will be needed to achieve the same cooling performance of water, in addition to limiting the possibility of thermal-waste recovery. However, in some situations where water is limited, air may still be the perfect option. Water cooling on the other hand, permits operation at much higher temperature levels and allows waste heat recovery to be employed more efficiently. Hence, air cooling is less favorable option in many cases. Many active cooling systems work in tandem with passive cooling elements to function more effectively. Therefore, the choice of the cooling medium is highly dependent on the PV system design requirements and the conditions at which the system operates.

4. Hybrid photovoltaic systems

The heat that is a by-product of electricity generation by PV cells can be utilized in hybrid system designs instead of simply dissipating it to the environment. Hybrid photovoltaic–thermal (PVT) systems offer a practical solution to increase the electrical power production from PV panels in addition to the recovery of heat extracted from the panels [17,18,23]. Waste heat recovery permits the utilization of waste heat to supply space or water heating in a way allowing improved overall system efficiencies to as high as 70% [18–24]. However, with most systems there are often instances where all of the heat can never be put to use, and so the overall efficiency of the system is usually lower. Furthermore, since the purpose of PV systems is to produce electricity, it may often be more desirable to use the PV by-product heat to generate supplemental electricity. There are several methods for utilizing waste-heat to produce electricity [24]. Hybrid PVT Systems are discussed in detail in the next section with various designs proposed by researchers to achieve cooling action and high overall system efficiency. In order to increase the electrical efficiency of PV cells and make good use of the incident solar radiation, it is most desired to remove the accumulated heat from the concealed PV surface and recover this heat appropriately. Hybrid PVT collectors are able to do so by simultaneously converting solar radiation available from the sun into electricity and heat.

The concept of PVT was initially addressed by Kern and Russell [17]. For a PVT module, the solar irradiation with wavelength between 0.6 and 0.7 μm is absorbed by the PV cells and converted into electricity, while the remaining irradiation is dissipated as heat. Consequently, PVT module could collect and convert higher fraction of solar energy that neither individual PV panel nor thermal collector do of equal absorbing areas [23–25], and therefore, offers a potential of creating low cost and highly efficient solution for heat and power generation. PVT systems are classified into different categories depending on the structure or functionality of the designs. In terms of heat extraction employed, PVT modules could be classified as air, liquid, heat pipe, phase change materials (PCM), and thermoelectric-based types, Fig. 4. The integration of thermoelectric generators with PV systems allows utilizing the PV by-product heat to generate supplemental electricity, hence improving the power generation of the system. While, other hybrid PV configurations offer both

electricity and heat capture simultaneously. In terms of the system structure, the modules could be classified as flat-plate, concentrated, and building integrated (BIPV) types. A comprehensive review of various methods employed for cooling of PV cells in addition to different hybrid PVT designs are presented in this paper.

4.1. Air-based PVT collectors

Air-based PVT collectors are formulated by incorporating air channels often present at the rear of a PV laminate allowing naturally or forced ventilated air to flow and extract accumulated heat through convective heat transfer. The use of forced air enhances heat extraction resulting in further improved performance of air PVT systems when compared with naturally ventilated ones [20]. Nevertheless, parasitic power losses are introduced due to the use of air blowers, hence affecting the net electricity generation. Several design concepts have been illustrated by researchers with respect to air flow patterns in addition to presence of front glazing to achieve optimum performance of PV modules, Fig. 5. Owing to minimal use of material and low operating costs among other PV cooling technologies, ventilated PVT and PV façade systems have found broad range of

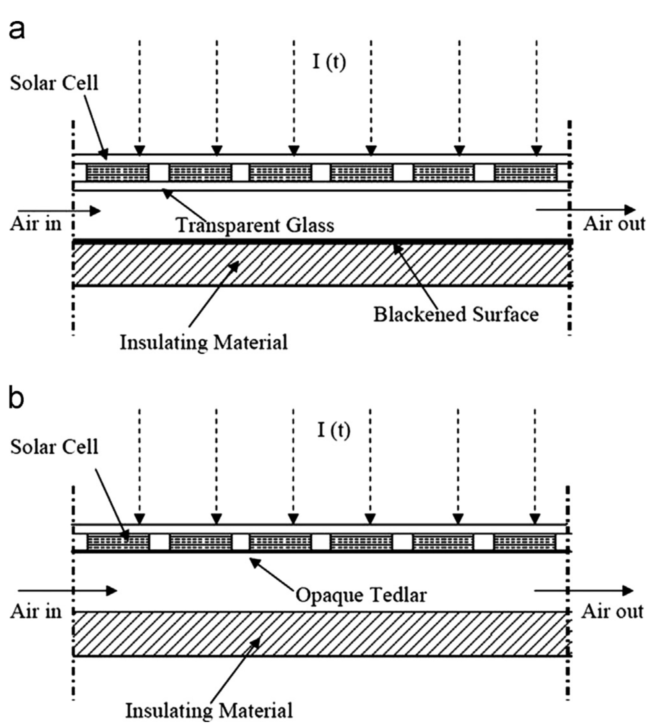

Fig. 6. (a) Glass-to-glass PV module with duct, (b) glass-to-tedlar PV module with duct [27].

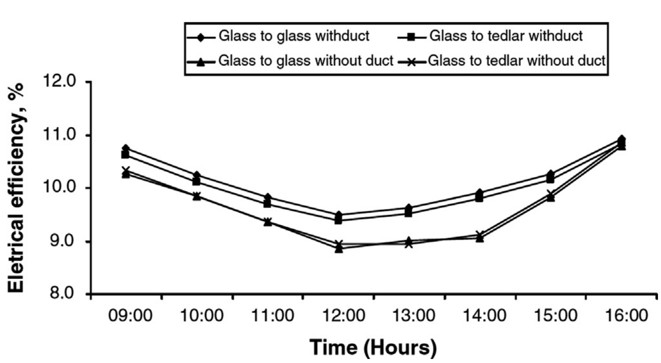

Fig. 7. Electrical efficiency of PV cells for collectors investigated in [27].

applications in which hot air is required for space heating, agriculture/herb drying, as well as electricity generation [18,26]. However, due to low density and small heat capacity of air, improvements in the practical performance of air-based PVT collectors are limited, making air less favourable option. Nonetheless, such designs are attractive in situations where water is limited. In the following section a review on the recent advancements as well the limitations of ventilated PVT and PV façade systems are presented.

Dubey et al. [27] studied analytically and experimentally different configurations of PV modules under typical New Delhi climatic condition in the month of April, Fig. 6. Four different configurations were investigated, namely, (1) glass-to-glass PV module with duct, (2) glass-to-glass PV module without duct, (3) glass-to-tedlar PV module with duct, and (4) glass-to-tedlar PV module without duct. Higher electrical efficiency and outlet temperature were achieved with the glass-to-glass PV module type with duct compared to the glass-to-tedlar type PV module with duct owing to radiation being transmitted through the back glass. Meanwhile, in the case of glass-to-tedlar the radiation is absorbed by the tedlar layer and conducted away resulting in higher cell temperature, Fig. 7. The theoretical models were experimentally validated and good agreement was observed. Improvement of 6.6% in the annual average efficiency was reported with the glass-to-glass type PV module with duct.

Numerical models of two low cost modification techniques to enhance heat transfer in air-based PVT collectors through natural ventilation were considered by Tonui and Tripanagnostopoulos [28]. The modifications consisted of a thin metal sheet suspended at the middle of the air channel (TMS), and a finned metal sheet at the back wall of the air duct (FIN), Fig. 8. The models were validated against the experimental data for both glazed and unglazed PVT collectors using a commercial poly-crystalline silicon (pc-Si) PV module rated at 46 Wp, and aperture area of 0.4 m^2 with a rectangular air duct channel of 0.15 m depth and good agreement between predicted values and measured data was observed. The effect of channel depth on the PV temperature was studied and results showed an optimum channel depth at which the PV module temperature was least, Fig. 9. Results showed that at a channel depth of 0.15 m, the unglazed TMS and FIN systems achieved reduced PV module temperature of about 3 °C compared to the reference system, which contributes to about 1–2% improvement the electrical efficiency. It was concluded that such modifications are suitable for building integration and can be applied in solar chimneys for natural ventilation of buildings.

The performance of a PVT air solar heater was studied analytically and experimentally considering various design parameters under controlled indoor conditions by Solanki et al. [29]. The prototype consisted of three modules of mono-crystalline silicon (mc-Si) solar cells, each rated at 75 Wp and have dimensions of 0.45×1.2 m mounted on a wooden duct allowing inlet and outlet air to pass below the PV modules to extract thermal energy from the back surface of the PV modules. The effect of the mass flow rate on the electrical, thermal, and overall efficiency at solar radiation intensity of 600 W/m^2 and inlet air temperature of 38 °C is shown in Fig. 10. It was concluded that enhanced performance of PV cells can be achieved through air cooling in which a temperature drop of about 10 °C at the PV cell level was achieved, Fig. 11. The reported electrical, thermal, and overall efficiency were 8.4%, 42%, and 50%, respectively.

Bambrook and Sproul [30] investigated experimentally the enhancements of both electrical and thermal energy of a PVT collector using air as a heat extraction medium. The cooling system comprised of an open loop single pass duct using extraction fan capable of producing high air mass flow rates (0.02–0.1 kg/s/m^2) at low input power (4–85 W), Fig. 12. Enhanced electrical power in excess of the fan requirements was reported for air mass flow rates ranging between 0.02 and 0.08 kg/s/m^2, with thermal efficiencies in the range

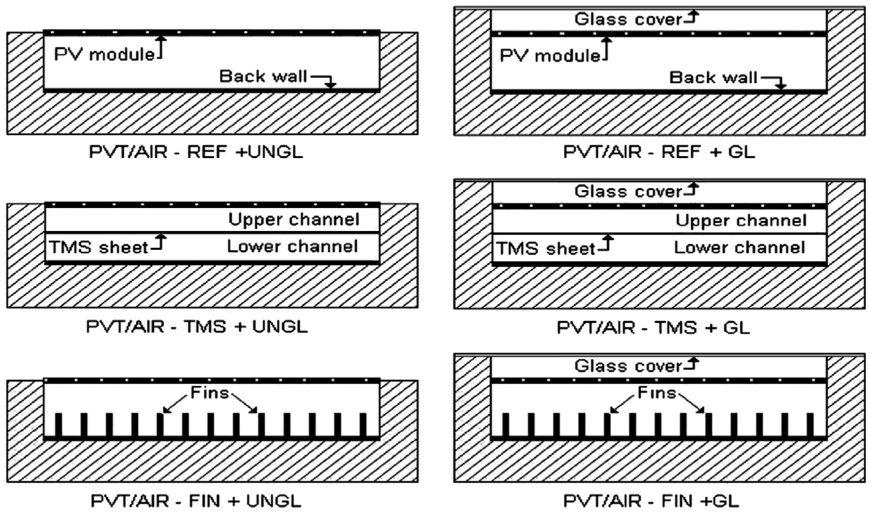

Fig. 8. Air-based PVT collectors with thin metal sheet (TMS) and finned metal sheet (FIN) [28].

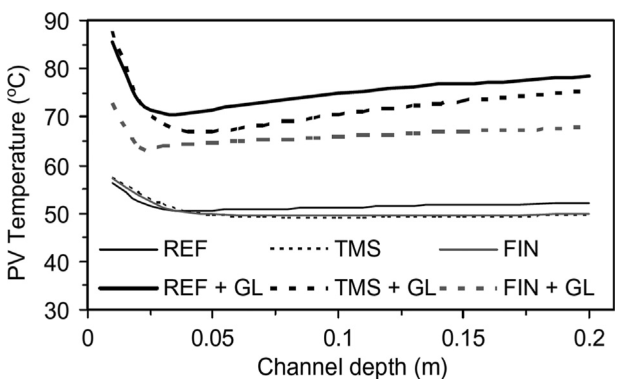

Fig. 9. PV surface temperature as function of air duct depth [28].

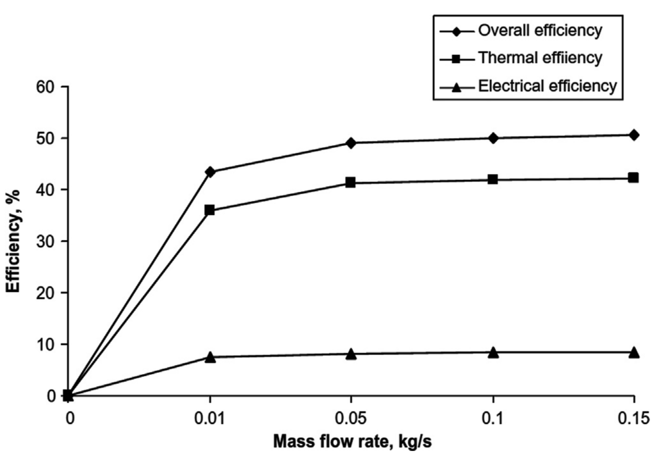

Fig. 10. Electrical efficiency variation with mass flow rate [29].

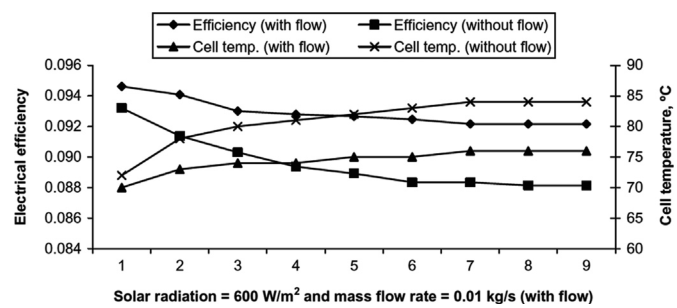

Fig. 11. Variation of electrical efficiency and cell temperature with and without flow in the duct [29].

of 28–55% and electrical PV efficiencies between 10.6 and 12.2% at midday, Fig. 13. The system performance was also compared with the energy requirement of the fan for a range of air mass flow rates. It is concluded that, the low grade thermal energy output makes such system suitable for residential applications, where the heat can be utilized for building heating.

Amori and Al-Najjar [31] investigated theoretically the performance of a hybrid PVT air collector for two different case studies under Iraqi climatic conditions. Improved thermo-electrical mathematical model of the PVT air collector considering the effect of radiative heat transfer in the air duct, and the convective heat transfer coefficient from both the PV module back surface and inner surface of insulation to the working fluid were accounted for. The effective sky temperature correlation for relative humidity was also adopted in the model [32]. Modified boundary conditions for better convergence and accuracy of the electrical model were also considered. The model presented was validated against previously published experimental results and theoretical simulations of similar designs by Joshi et al. [33] and Sarhaddi et al. [34], and better alternative amongst the existing models was observed. The electrical and thermal efficiencies for the two cases considered were 12.3% and 19.4% for the winter day, while that for the summer day were 9% and 22.8% respectively. Although the output power in the summer was observed to be higher than that in the winter (1.7 times at solar noon), the efficiency recorded in winter was higher due to the negative temperature coefficient of efficiency and higher fill factor.

Recently Amori and Abd-AlRaheem [35] have carried out a quantitative comparative study on different conceptual hybrid PVT collectors for Iraq climate conditions. Four different types of air-based PVT collectors were adopted in experimental work, namely, Model I: PV modules without cooling, Model II: Hybrid PVT collector with single duct double pass, Model III: Hybrid PVT collector with double duct single pass, and Model IV: Hybrid PVT collector with single duct single pass. A DC fan of power of (6 W) at the ducts' outlet was used to pull air. A mathematical expression of the PVT collector model IV was also developed based on energy balance to analyse the thermal and hydraulic performances of the model. Model IV achieved better electrical performance compared to model II and III, while the overall efficiency of model III was higher than that of model II and model IV due better heat extraction. Measurements also showed that optical losses were

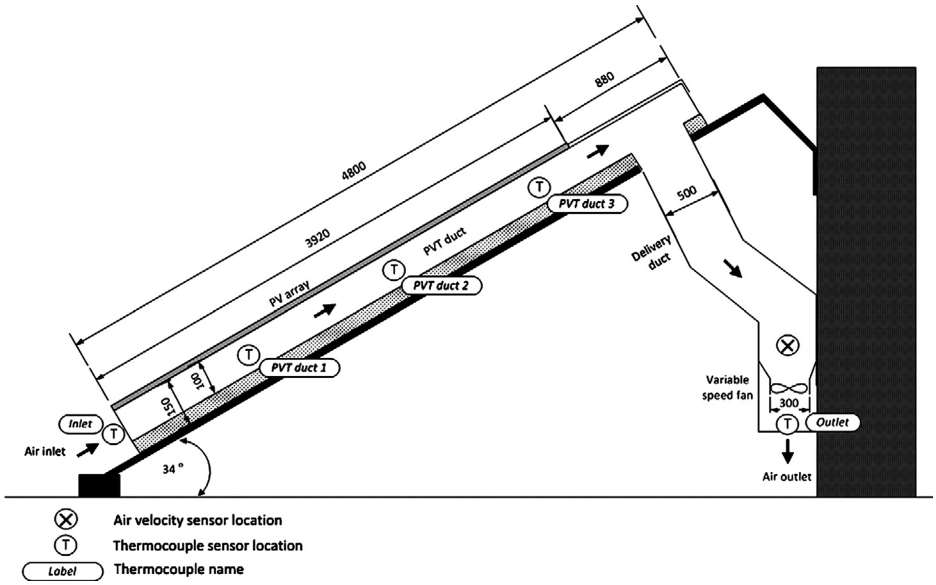

Fig. 12. Air-based PVT with open loop single pass duct [30].

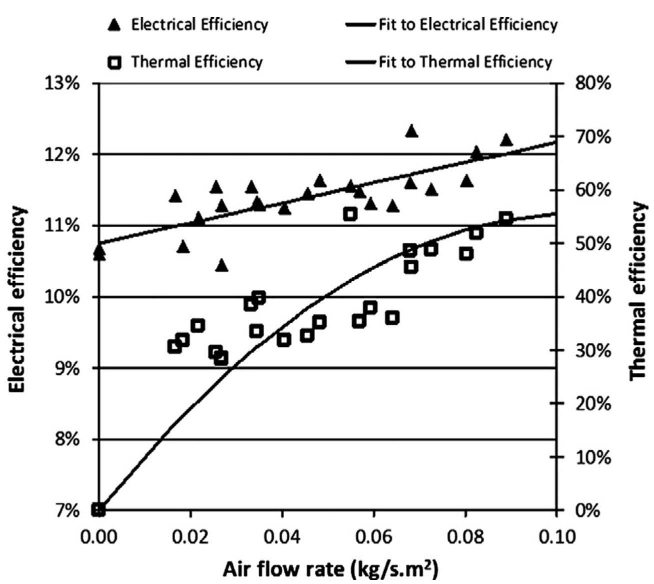

Fig. 13. Electrical and thermal efficiency variation of PVT with open loop single pass duct [30].

introduced due to presence of glass cover in models II and III as the electrical efficiency deviated before and after solar noon when compared to model I, which agrees with the findings in Ref. [36].

Yun et al. [37] investigated a ventilated PV façade system considering building characteristics and façade configuration for both preheating during winter and natural ventilation in summer, in addition to cooling of PV modules. The system incorporated transparent windows, opaque PV panels with air gap and concrete composite wall, and air dampers, Fig. 14. The researchers introduced the effectiveness of a PV façade (PVEF) parameter to evaluate the building performance in terms of heat transmission, ventilation, and daylight, in addition to the electrical efficiency of the PV modules. Results for the hottest recorded day showed an approximate improvement of 15% of PV module efficiency through the ventilated system when compared with that without ventilation, Fig. 15.

Sukamongkol et al. [38] investigated the dynamic performance of condenser heat recovery with air PVT collector for desiccant regeneration to reduce energy consumption of air conditioning for a room in tropical climates. The system comprised of a living space, desiccant dehumidification and regeneration unit, air conditioning system, PVT collector, and air mixing unit. Warm dry air of 53 °C and 23% relative humidity was reported from the measurements. In addition, energy saving in air condition of about 18% was reported through such integration. However, electrical efficiency of only 6% of the daily total solar radiation was recorded.

Temperature prediction of a multi-junction solar cell based on passive cooling was performed through theoretical thermal modelling by Min et al. [39]. A linear relationship between the heat sink area and the concentration ratio was observed in order to maintain acceptable cell temperature. Recently, active air cooling of concentrator multi-junction solar cells by convection and surface radiation was studied theoretically by Al-Amri and Mallick [40]. In their study a triple-junction GaInP/GaAs/Ge solar cell with a Cu–Ag–Hg front contact was considered where air was forced within ducts underneath aluminium base plate. Noticeable effect of surface radiation on the temperature of the PV cell was observed which agreed with the findings of a study conducted by Moshfegh and Sandberg [13]. Analysis also revealed that increasing the emissivity of the duct walls promoted the effect of the surface radiation. Simulation results under concentration ratio of 100 × predicted a drop in solar cell temperature from 240 °C to 150 °C as the emissivity was increased from 0 to 0.98. The effect of thermal conductivities of solar cell holders and accessories in addition to air inlet velocity, channel width, and thicknesses were also examined and found to have great influence on the maximum cell temperature and critical concentration ratio.

Utilizing micro-channels, Agrawal and Tiwari [41] presented the concept of series and parallel air flow arrangement of micro-channel solar cell thermal tiles. The system comprised of air channels of depth 500 μm made between a 0.0144 m^2 cell and tedlar allowing for the thermal resistance of tedlar to be eliminated, Fig. 16. Nine rows of four series-connected micro-channel solar cell thermal (MCSCT) tiles were connected in parallel to form a micro-channel PVT (MCPVT) module. Performance of the MCPVT in terms of overall energy, exergy and exergy efficiency was compared with that of single channel PVT module studied by Dubey et al. [27] with same (micro depth) flow rate. Results revealed that the MCPVT module achieved higher overall exergy efficiency, Fig. 17. Agrawal and Tiwari extended their study to validate their aforementioned MCPVT module, in addition to other MCPVT module configurations being investigated [42].

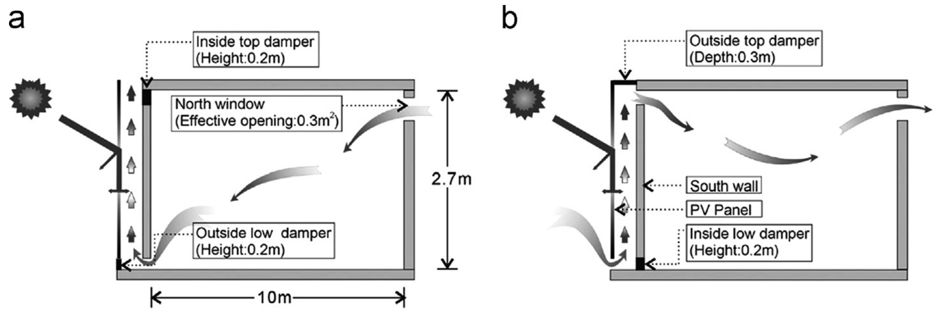

Fig. 14. Ventilated PV façade system (a) summer, (b) winter [37].

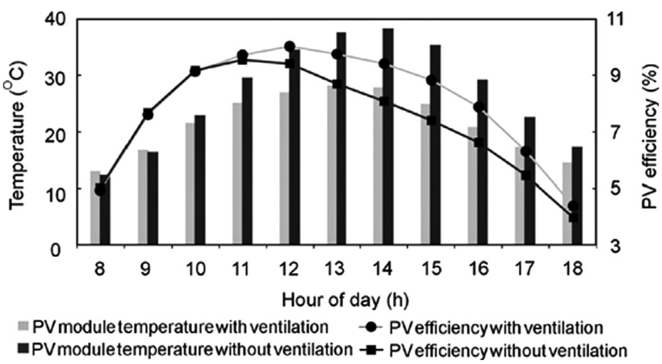

Fig. 15. PV efficiency and module temperature of ventilated PV façade [37].

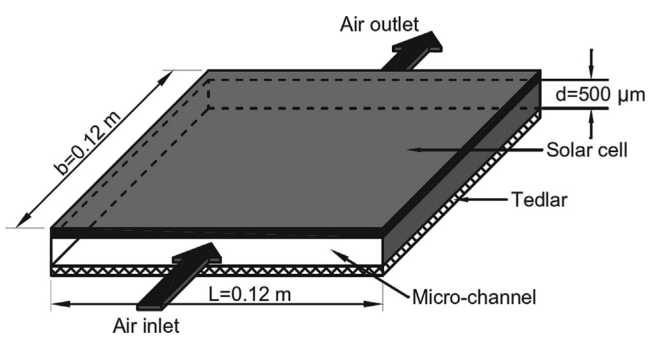

Fig. 16. Micro-channel solar cell thermal (MCSCT) tile [41].

Theoretical analysis and optimization were carried out by Rajoria et al. [43] adopting the designs proposed in Ref. [42], Fig. 18. Due to low value of bottom and side losses, case-II achieved the highest value of overall thermal energy among other arrays. Nevertheless, higher grade of energy was achieved through the configuration in case-III with average electrical efficiency of 11.3% resulting in further 12.9% improvement in overall exergy efficiency than that of case-II. Owing to increased number of PVT module connected in series, case-III achieved the highest outlet air temperature than other designs investigated.

In a recent study by Rajoria et al. [44] utilizing the same concept, the flow arrangement was modified such that air was passed under two parallel-connected columns of 18 modules each having 36 series-connected PVT tiles. Results were compared with array in case-III in [43], and the new design was observed to be more efficient. Further improvements in electrical efficiency, outlet air temperature, and annual overall exergy efficiency of 6.5%, 18.1%, and 10.4% respectively were observed compared to that of case-III under the same climatic conditions. The study was extended to investigate the Co_2 mitigation and environmental cost utilizing exergoeconomic analysis to reflect the financial gain/saving that can be obtained for four different cities in India. On a similar study, carbon credit analysis for different air-based PVT arrays was conducted, enabling price comparison between systems in respect to Co_2 emissions for the city Srinagar (India) [45].

Three heat exchanger designs, namely, V-groove, honeycomb and stainless steel wool incorporated at the rear of PV module were investigated experimentally [46], Fig. 19. Under irradiance of 828 W/m^2 and mass flow rate of 0.11 kg/s PVT module with honeycomb heat exchanger achieved better performance with reported thermal and electrical efficiencies of 87% and 7.13% respectively. This was attributed due to larger surface area in direct contact with the PV module in addition to the uniform air flow resulting in enhanced heat transfer from the PV module to flowing air. Air PVT and ventilated PV façade systems have found broad range of applications offering a simple mechanism to cool PV cells and low grade thermal energy for space heating in residential applications. Nevertheless, the low density and small heat capacity of air limits the improvements in the performance of air PVT collectors, hence making air less favourable option.

4.2. Liquid-based PVT collectors

At high operating temperature conditions, air cooling fails to accommodate the temperature rise at the surface of PV cells causing critical drop in their conversion efficiency. Liquid cooling offers a better alternative to air cooling utilizing coolant as heat extraction medium to maintain desired operating temperature of PV cells and a more efficient utilization of thermal energy captured [18,47–49]. Liquid-based PVT collectors are superior to air-based ones due to higher specific heat capacity of coolants employed leading to further improved overall performance [47,20]. In addition, liquid-based PVT collectors offer less temperature fluctuations compared to air-based PVT making them more favourable [47]. The most common liquid-based PVT collector design comprises of metallic sheet-and-tube absorber in which heat extraction is attained via forced fluid circulation through series/parallel-connected pipes adhered to the rear of PV collector [18,51–53]. As a result improved conversion efficiency is achieved and useful thermal energy is made available for utilization in domestic and industrial applications. Fluid circulation in such type of collectors is accomplished utilizing either gravity-assisted circulation or circulation pumps. Liquid-based PVT systems are commonly distinguished according to working fluid employed [50]. Water is the most common fluid employed; however, refrigerants that are able to undergo phase change at a relatively low temperature have been adopted in many systems recently. In this section a review on liquid-based PVT collector system utilizing water and other liquid refrigerants as heat extraction fluids is presented.

4.2.1. Water-based PVT collectors

Several water-based PVT collector designs having different flow patterns have been introduced and investigated both theoretically

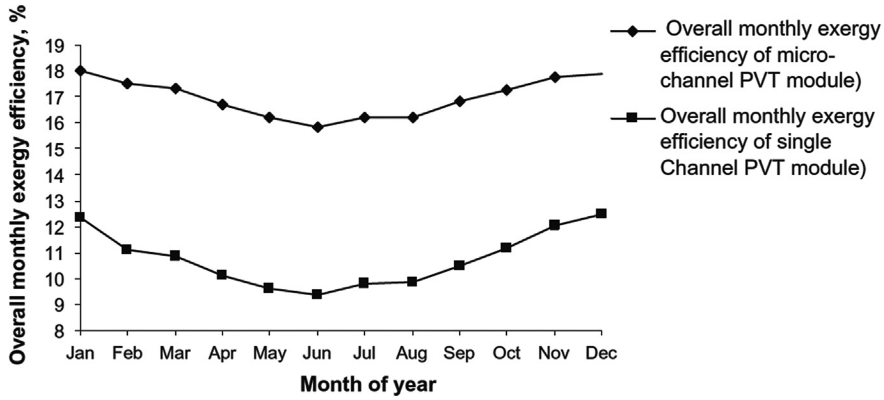

Fig. 17. Exergy efficiency utilising mirco-channel solar cell thermal (MCSCT) tile with air cooling [41].

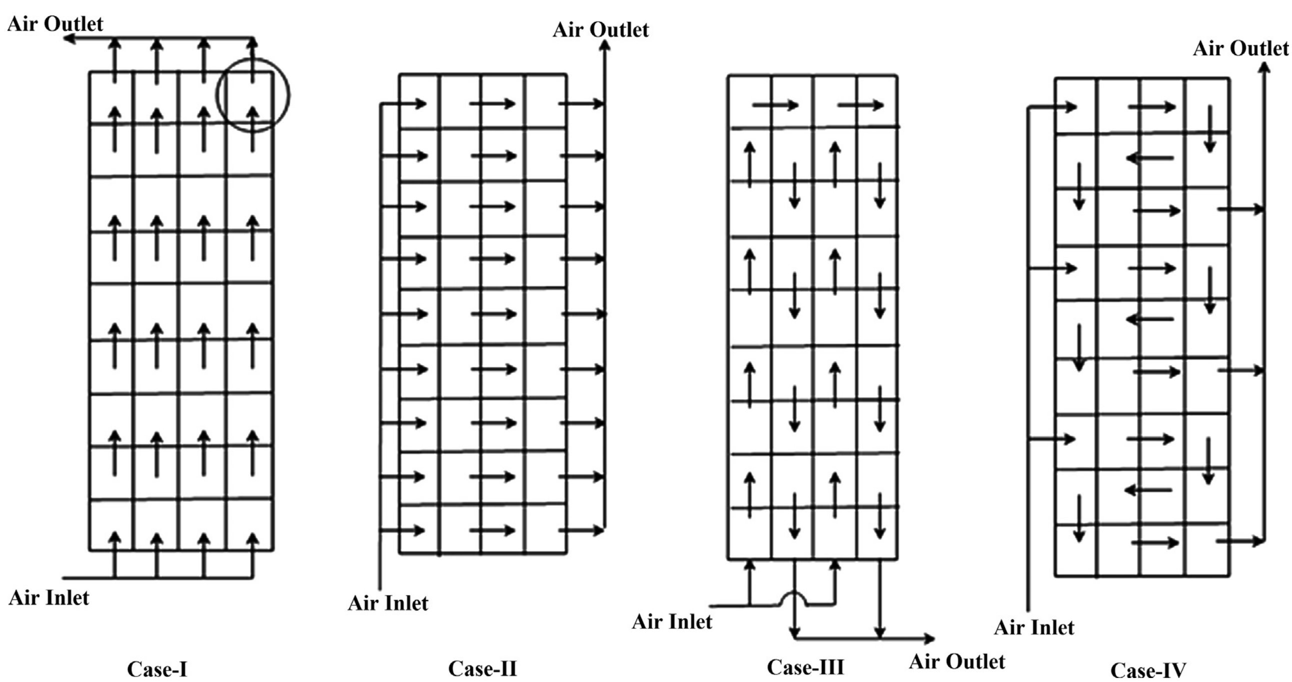

Fig. 18. Series and parallel arrangement of micro-channel solar cell thermal tiles with air cooling [42,43].

and experimentally to achieve efficient cooling of PV cells, Fig. 20. However, the most common collector design studied consists of a PV module attached to an absorbing collector with serpentine of a series or parallel tubes at the rear surface of PV modules (sheet-and-tube), Fig. 21. The PVT water collector operates such that water is forced to flow across tubes extracting the excessive heat from the PV cells, hence reducing the operating temperature of PV cells and transferring heat to be utilized for water and space heating applications. Researchers have identified several environmental and design parameters affecting the performance of such type of collectors including; mass flow rate, water inlet temperature, number of covers, absorber to fluid thermal conductance, PV cells packing factor, collector length, duct depth absorber plate design parameters [31,54].

An early theoretical study on combined PVT water system was conducted by Garg and Agarwal [55]. The system comprised of a roof-mounted flat plate thermal collector with PV laminate pasted on top of an absorber plate, a storage tank, water pump for water circulation through pipes, and a control system to control on/off switching of the pump. Simulation was performed for different operating and design parameters including, PV cell areas, mass flow rates and water masses. Zondag et al. [52] performed numerical analysis on water-based PVT collectors having different water flow patterns that were discussed by de Vries in [53]. Results in terms of electrical efficiency revealed that sheet-and-tube achieved conversion efficiency of 9.7%, higher than that of PVT collectors with water channel, free flow, or two-absorber. However, the thermal efficiency predicted of the sheet-and-tube collector was about 13–21% less than that of other designs. Huang et al. [56] compared the performance of an integrated PVT solar system with conventional solar water heater experimentally. Polycrystalline PV cells were laminated on a thermal collector comprising of a corrugated polycarbonate panel and thermal insulation layer attached at rear to form a PVT module. Thermal efficiency of 38% was reported (about 76% of conventional solar water heater) electrical efficiency of 9%, and primary-energy saving efficiency of 60%, higher than either sole water heater or PV systems.

A PVT collector utilizing aluminium-alloy flat-box for domestic water heating was constructed and experimentally investigated [57,58]. PV cells were adhered on the surface of the aluminium alloy absorber which comprised of multiple extruded aluminium alloy box-structure modules having their ends connected to two aluminium traverse headers in which water circulation was

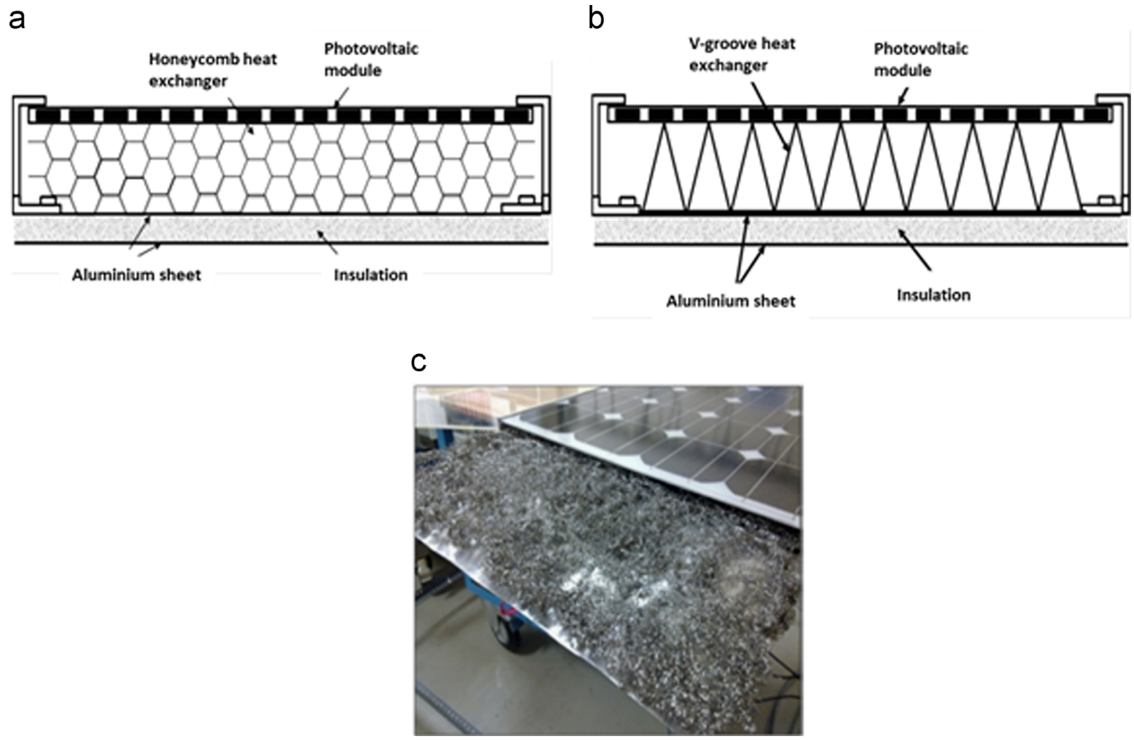

Fig. 19. PV modules with different heat exchanger designs (a) honeycomb, (b) V-groove, (c) stainless steel wool [46].

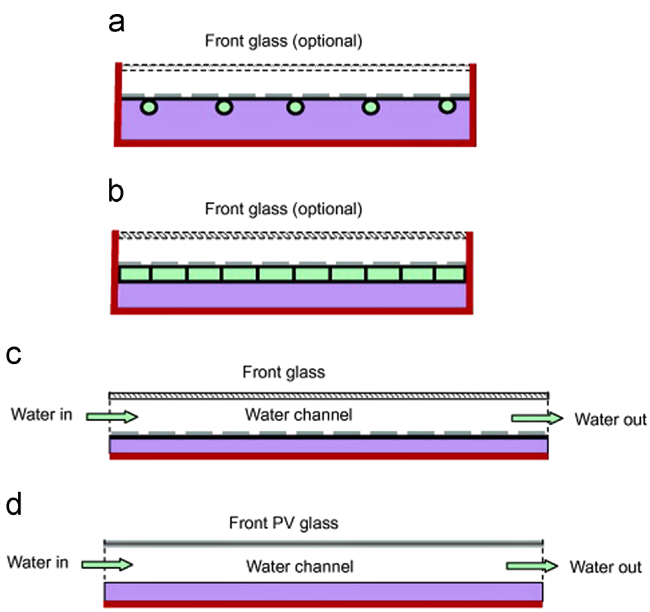

Fig. 20. Different configurations of water-based PVT collectors [48].

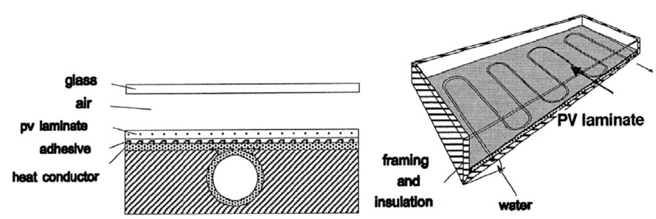

Fig. 21. Sheet-and-tube PVT collector [52].

achieved through the themosyphon effect, Fig. 22. A thermal simulation model of the hybrid system was developed and results agreed well with the measured data [57]. The validated model was used to examine the steady state performance of the collector under different operating conditions of China. Under 800 W/m^2 of solar irradiation, 20 °C ambient air temperature, 2.5 m/s wind speed, and water mass flow rate of 76 kg/(h m^2) the ranges of the averaged daily thermal and electrical efficiencies were 37.6–48.6% and 10.3–12.3%, respectively [57]. Such variation in efficiencies was observed to be dependent on the corresponding water-temperature and the level of solar radiation. Moreover, incorporation of anti-freeze closed-loop design was suggested to overcome water-freezing problems inside flow channels during severe cold days in winter. He et al. [58] observed a slightly lower value of the overall thermal-absorption of hybrid PVT system compared to conventional solar hot water collector attributed to lower optical absorption of the PV module as compared to the mat-black thermal absorber surface. However, energy-saving efficiency of 52% was achieved, which was above the conventional solar hot-water collector and slightly higher than the performance of the unglazed PVT system using plastic channel absorber under forced circulation tested by Huang et al. [56]. In a latter study by Chow et al. [59], computer simulation model of a vertical wall-mounted water-based PVT was developed. The annual average thermal and cell conversion efficiencies of PVT collector with flat-box type thermal absorber and polycrystalline silicon cell were 37.5% and 9.39%, respectively.

Ji et al. [60] presented a numerical model of wall-mounted water-based PVT collectors for electricity and hot water supply, in addition to improving the thermal insulation of the building envelope. The work adopted the PVT collector design presented earlier in [57,58]. Air gap was incorporated between the front glazing and the PV surface to aid ventilation, which was addressed by Brinkworth et al. [61] to assist reduction in operating temperature of PV modules. The BIPVT system comprised of six PVT collectors each of aperture area 1.173 m^2, a 420 l water storage tank, a water circulation pump and connecting pipes, Fig. 23. The influence of packing factors, water flow rate, and water delivery pipe size, on the electrical and thermal efficiencies was analysed to enable optimal set of design parameters to be identified. Results

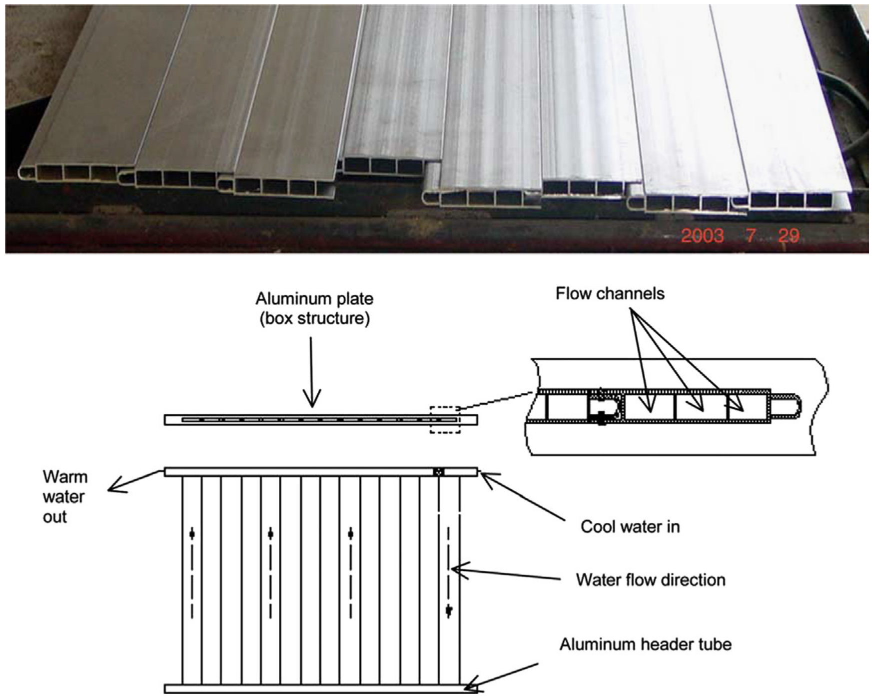

Fig. 22. Flat-box aluminium-alloy heat exchanger [57,58].

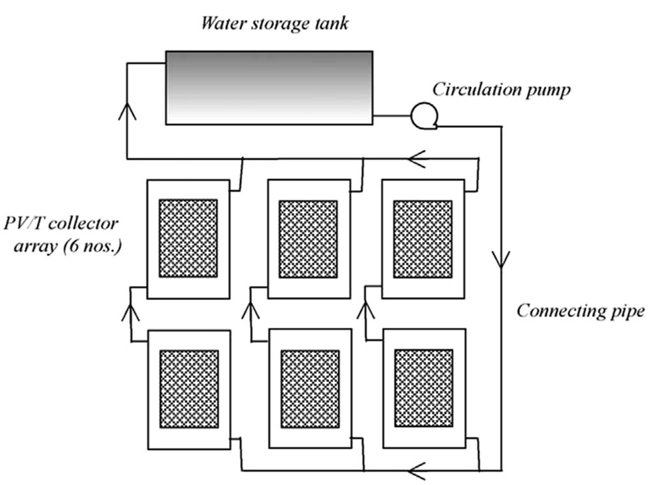

Fig. 23. Wall-mounted water-based PVT collectors [60].

revealed that as the pipe diameter increased from 0.01 to 0.02 m, the required pumping power reduced dramatically. Nevertheless, further increase in the pipe diameter results in increased thermal loss at the exterior pipe surface. The effect of water mass flow rate was observed to improve the thermal efficiency and PV cooling as the heat removal factor was enhanced. However, the advantage of increased flow rate diminishes when the critical flow rate is exceeded, thereby decreasing thermal efficiency.

The performance of water-based PVT collectors having different configurations of absorber collectors was studied theoretically by Ibrahim et al. [62], Fig. 24. The PVT collector comprised of poly-crystalline PV cells with hollow tubes attached underneath. Under water flow rate of 0.01 kg/s spiral flow design proved to be the best design with the highest thermal and cell efficiencies of 50.12% and 11.98% respectively and output temperature of 31 °C. Different output temperatures were observed and attributed to the design configuration of the absorber, in which the closer spacing between tubes enabled more heat to be absorbed. In a further study, Ibrahim et al. [63] investigated the water type PVT collector with spiral flow design experimentally and compared it with single pass rectangular tunnel absorber collector for air flow. Electrical and thermal efficiency of 64% and 11% respectively were achieved under same water flow rate in the previous theoretical study. Compared to the single pass rectangular collector absorber with water flow, spiral flow design offers better heat extraction and overall efficiency having low surface temperature.

Based on a theoretical model, Dubey and Tiwari [64] analysed the thermal energy, exergy and electrical energy yields of water-based PVT collectors by varying the number of collectors in use, series/parallel connection patterns, and operating conditions. The study concluded that the decision of PV cells covering factor would depend on the system requirements, in which partially covered by PV cells would be beneficial when hot water production is a priority. On the other hand, fully covered collectors enhanced electrical energy yield leading to higher exergy efficiency. Dubey and Tiwari extended their work to identify the economical/environmental benefits of their system through evaluation of the optimum hot water withdrawal rate [65].

Brogren and Karlsson [66] used active water cooling method to cool a hybrid PVT system with stationary parabolic reflectors for low concentration ratio. The system consisted of a row of mono-crystalline silicon cells laminated on a copper fin thermal absorber with a water tube welded on the back. Results of the experiment under 3 × concentration ratio measured a short-circuit current of 5.6 A compared to identical module without concentration having a short-circuit current of 3 A, hence showing a true optical concentration of only 1.8 ×. Brogren and Karlsson justified the losses were attributed to geometrical imperfections of the concentrating element and optical losses in the reflector and the cover glazing. Meanwhile, significant amount of thermal energy 3–4 times the electric energy was produced at a water temperature of 50 °C.

Zhu et al. [67] conducted experimental work investigating dielectric liquid immersion cooling for concentrator PV system using 250 × dish concentrator. Mono-crystalline silicon PV cells with back contacts were mounted on copper-clad electrically insulating substrates to form modules, each having 88 cells connected in series. Under 250 suns with direct normal irradiance

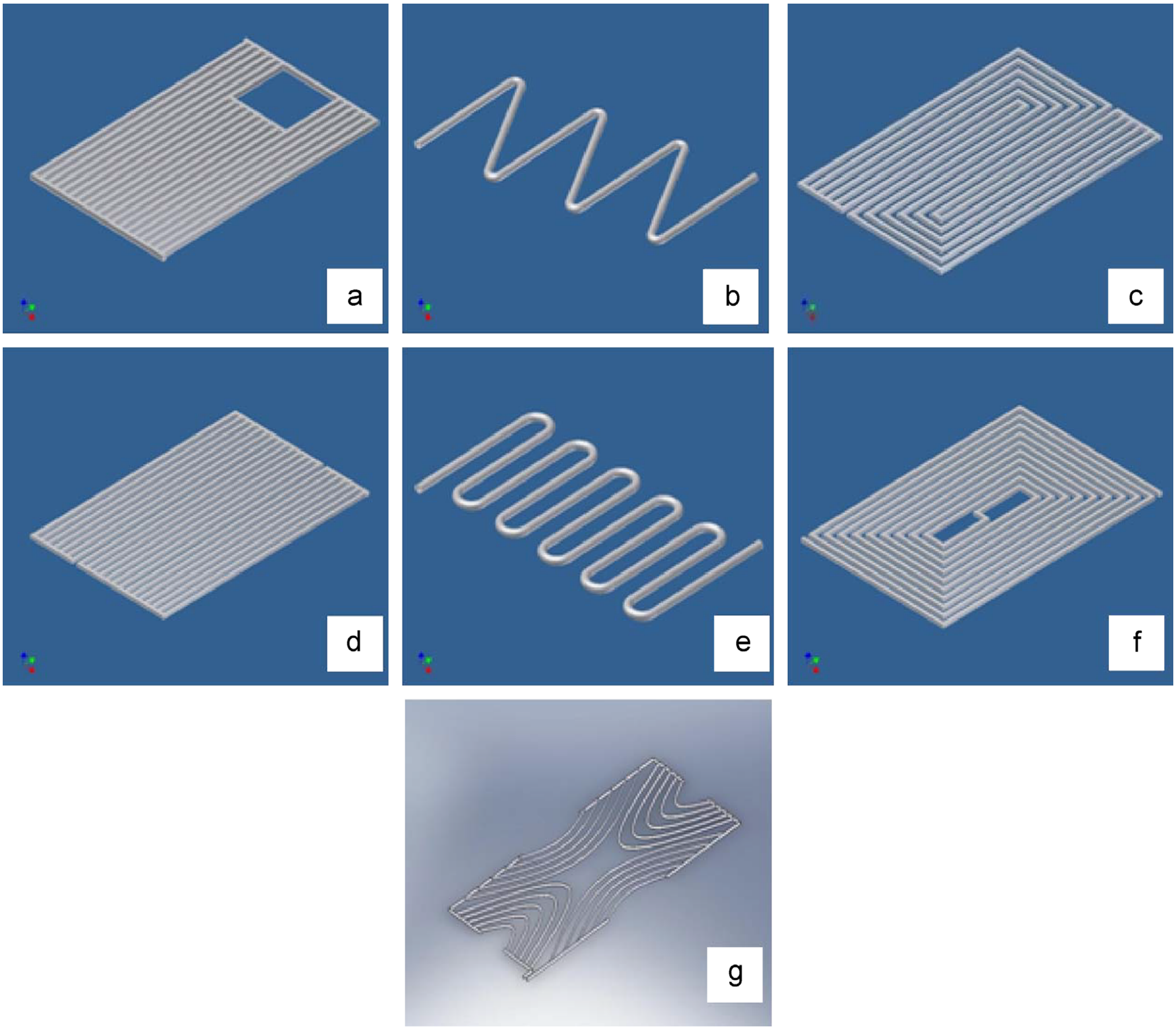

Fig. 24. (a) Direct flow design, (b) serpentine flow design, (c) parallel–serpentine flow design, (d) modified serpentine–parallel flow design, (e) oscillatory flow design, (f) spiral flow design, (g) web flow design [62].

of 900 W/m^2, cooling water inlet temperature of approximately 31 °C and ambient temperature around 17 °C peak module temperature of 49 °C was observed. Moreover, temperature distribution difference along the surface of less than 4 °C was attained. Due to eliminated contact thermal resistance of back cooling, liquid immersion facilitated improved cell performance to be achieved. In a more recent work, improvement in electrical efficiency of about 8.5–15.2% was reported through 1.5 mm thickness liquid layer over the cell surface by Han et al. [68].

Prudhvi and Sai [69] proposed improving the efficiency of the PV by active cooling to reduce the temperature losses considerably and decrease reflection losses. A thin layer of water to flow on the surface of the solar panel was investigated. The system considers closed circuit flow, whereas "Ground Water Tunnelling" mechanism was applied to cool water absorbing the heat from the surface of the PV cells. Practical calculation based on the developed model presented a net 7.7% improvement in efficiency.

4.2.2. Refrigerant-based PVT collectors

Refrigerant fluids are normally used in systems combining PVT collectors and solar-assisted heat pumps (SAHP), in which the PVT collector serves as an evaporator where the refrigerant absorbs thermal energy available at the PV cells [70,71]. Low evaporation temperature (0–20 °C) of refrigerant allows efficient cooling of PV cells to be achieved leading to significant increase in the performance [25,70,71].

The performance of PVT solar-assisted heat pump co-generation system was investigated theoretically and experimentally by Ji et al. [72]. The system comprised of nine (3 × 3) mono-crystalline PVT collectors serving as direct-expansion evaporators for the heat pump in which R22 refrigerant inside copper coil vaporizes at low temperature transferring absorbed heat to the condenser section, Fig. 25. Dynamic distributed model was developed to predict various parameters including the pressure distribution of the PV evaporator and along the copper coil attached, temperatures of PV cells and base panel thermal collector, thermal and electrical efficiencies of the system, in addition to vapour quality and enthalpy. Validation of the simulation results exhibited good agreement with measured data except for the pressure drop of the PV evaporator which was found much higher than the simulation prediction attributed to underestimation of the saturated temperature gradient and higher temperature gradient along the copper coil observed during the experiment. Under solar irradiation of 840 W/m^2 and ambient

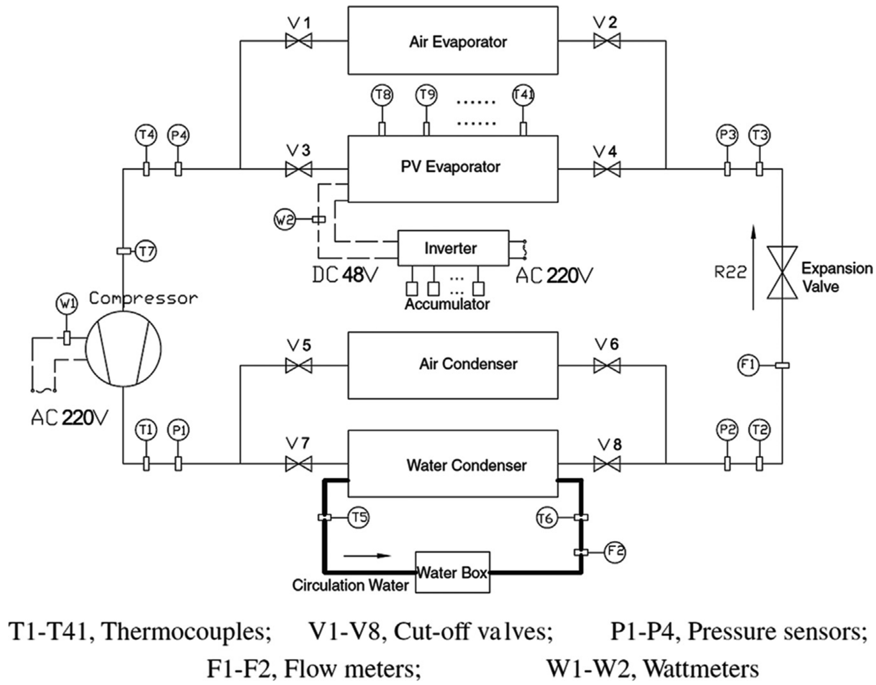

Fig. 25. Schematic diagram of PV solar-assisted heat pump [72].

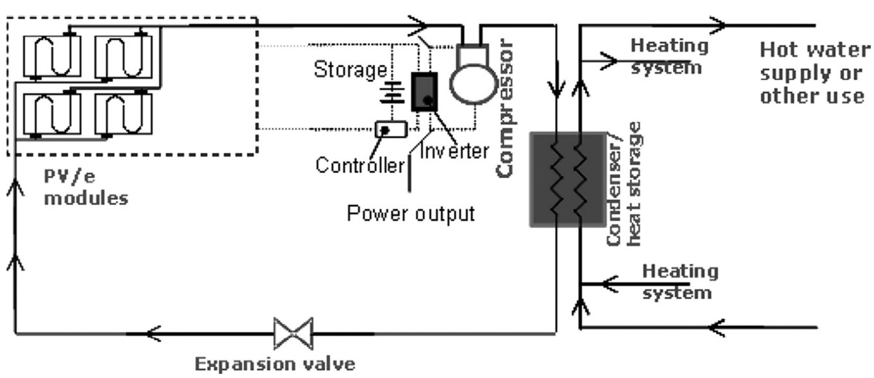

Fig. 26. PV/evaporator heat pump system [25].

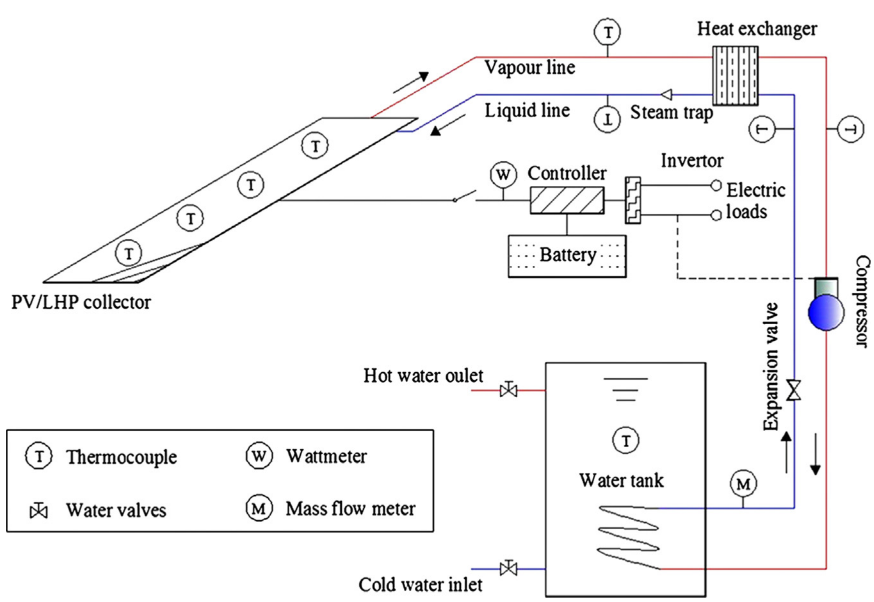

Fig. 27. PV/loop-heat-pipe (PV/LHP) heat pump solar system [73].

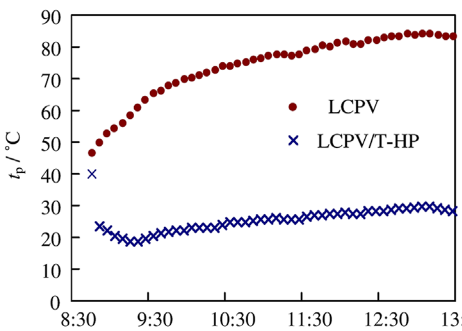

Fig. 28. PV cell operating temperature of low concentrating PVT integrated heat pump (LCPVT-HP) [75].

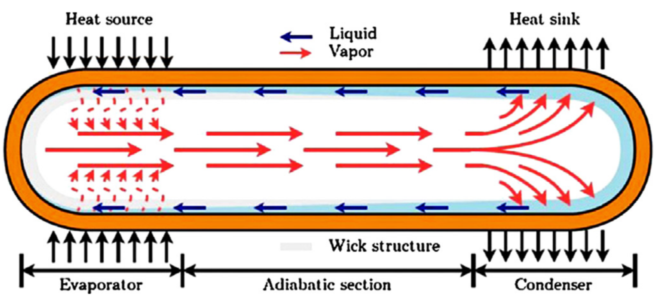

Fig. 29. Schematic diagram of heat pipe [18].

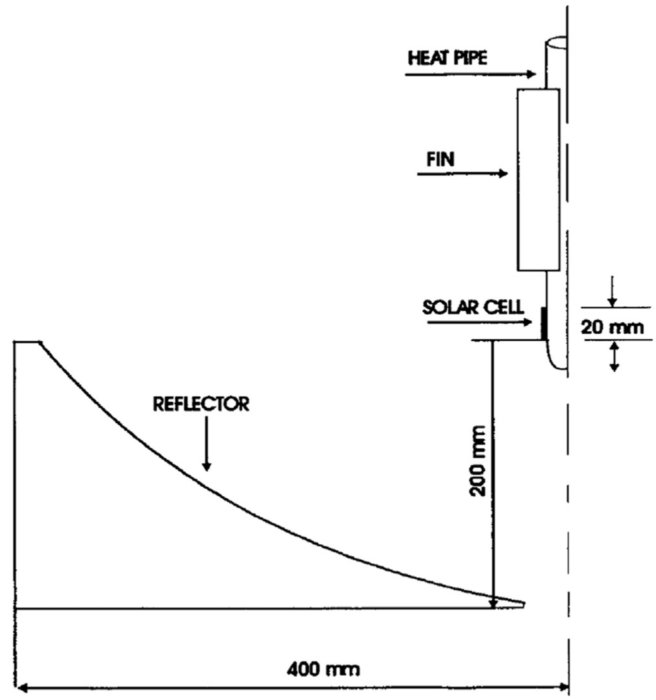

Fig. 31. Cooling of low concentrator PV cell with heat pipe extruded fin [79].

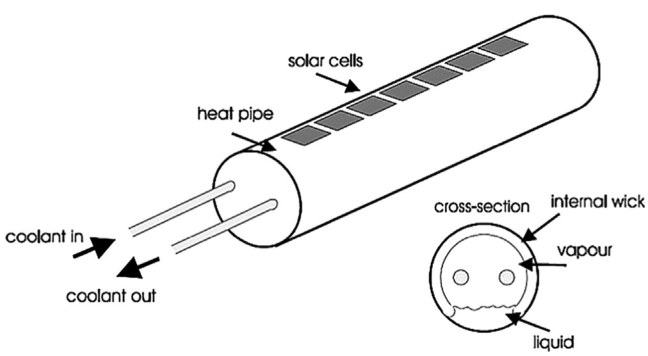

Fig. 30. Heat pipe cooling of PV cells [77].

temperature of 14 °C, the electrical and thermal efficiencies were 12% and 50% respectively implying enhanced cooling effect of the PV.

A novel PV/evaporator (PV/e) roof module for electricity generation and acting as an evaporator of a heat pump system was designed by Zhao et al. [25], Fig. 26. The performance was evaluated theoretically with R134a refrigerant based on various parameters including, top cover material, PV cells technology, and evaporation and condensation temperature of the heat pump. An optimized system configuration comprising of mono-crystalline PV cells, borosilicate top cover, evaporation and condensation temperatures of 10 °C and 60 °C respectively was suggested. The PV/e heat pump system was simulated under typical Nottingham (UK) weather conditions, and thermal and electrical efficiencies of 60.93% and 9.21% respectively were reported.

Improved performance of PVT collector is attained through utilising refrigerant cooling. Nevertheless, the practical feasibility of such systems encounters several challenges including, unbalanced refrigerant distribution, possible leakage of refrigerant, and maintaining pressurization and depressurization at different parts of the system [18,73,74]. In attempt to override such challenges, Zhang et al. [73] presented a novel PV/loop-heat-pipe (PV/LHP) heat pump solar system, Fig. 27. The design utilized loop heat pipe structure with three-ways tube combining the PVT module and the heat pump operations to overcome 'dry-out' problem encountered in conventional heat pipe cooling. Theoretical evaluation and experimental tests were conducted to define the performance of the system in terms of thermal and electrical efficiencies, and the system's overall performance coefficient. Predicted simulation results showed fair agreement with data measured. Parametric analysis on the impact of several operational parameters including; solar radiation level, ambient temperature, air velocity, evaporation temperature of heat pump, top glazing cover, and heat pipe absorbing number was performed using the validated model. Results under laboratory condition reported electrical, thermal, and overall efficacies of about 10%, 40%, and 50%, respectively. Overall coefficient performance of about 8.7 was measured contributing to improvement of two to four times than that for conventional solar/air heat pump water heating systems.

In a similar concept, Xu et al. [75] adopted refrigerant cooling to absorb heat from PV cells under low concentration using parabolic concentrator reflecting the incident sunlight onto the surface of PVT collector. Under climatic conditions of Nanjing (China) and low concentration, the PVT integrated heat pump (LCPVT-HP) achieved an electrical efficiency of 17.5%, which was observed to be 1.36 times higher than that of LCPV system without cooling. The effective cooling of refrigerant can be seen clearly in Fig. 28, where comparison between base panel temperature of the LCPVT with and without the presence of cooling is presented.

Liquid cooling offers a better alternative to air cooling utilizing coolant as heat extraction medium to maintain desired operating temperature of PV cells and a more efficient utilization of thermal energy captured. In addition, liquid-based PVT collectors offer less temperature fluctuations compared to air-based PVT making them more favourable in aiding a homogenous temperature distribution on the surface of PV modules. The low evaporative temperature (0–20 °C) of refrigerants allows efficient cooling of PV cells to be achieved leading to improved performance compared to water cooling. Nevertheless, the practical feasibility of such systems encounters several challenges as discussed earlier.

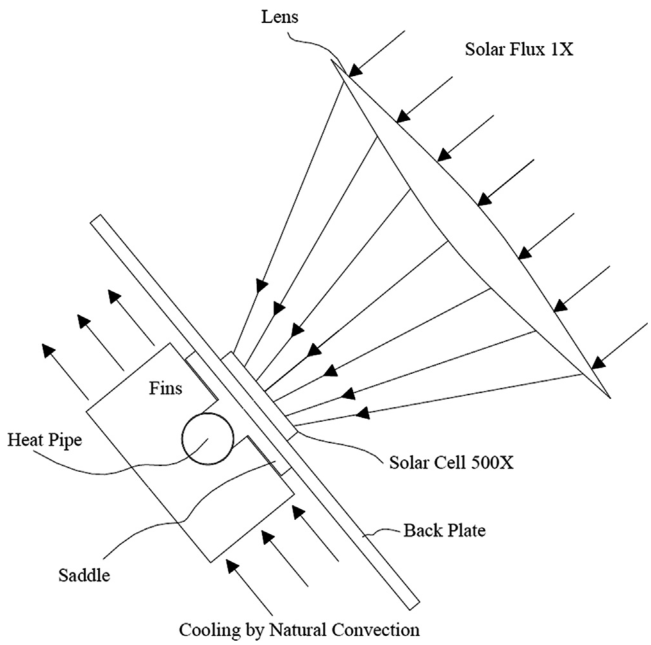

Fig. 32. Cooling PV concentrator through copper/water heat pipe with aluminium fins [81].

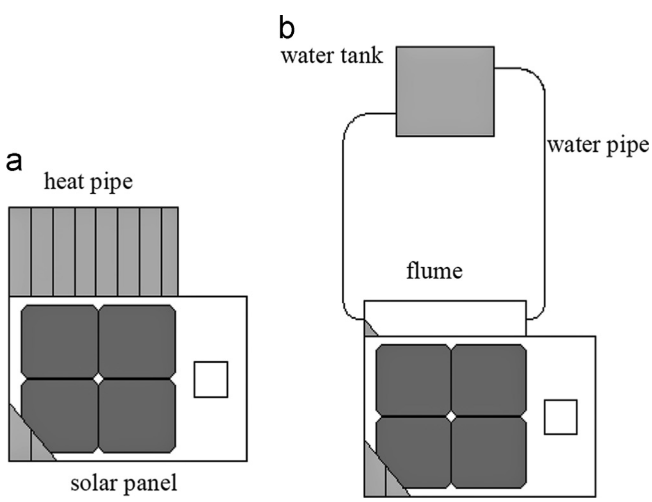

Fig. 33. Micro heat pipe array cooling for conventional flat-plate PV module using (a) air, (b) water [83].

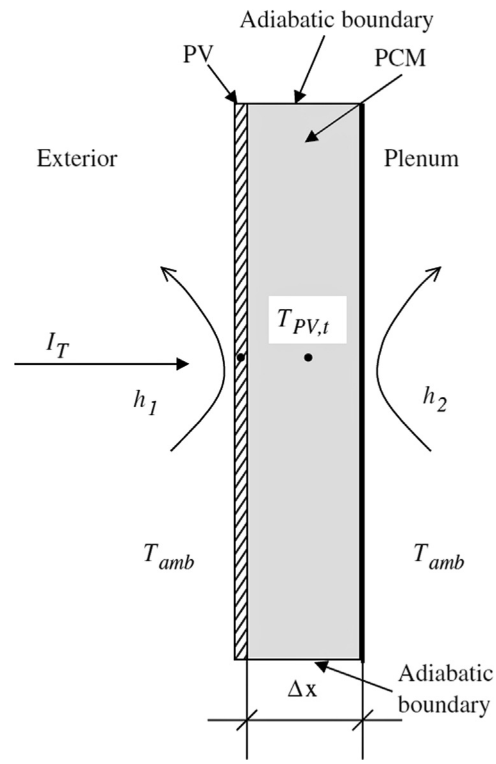

Fig. 34. Schematic drawing of a PV/PCM system [89].

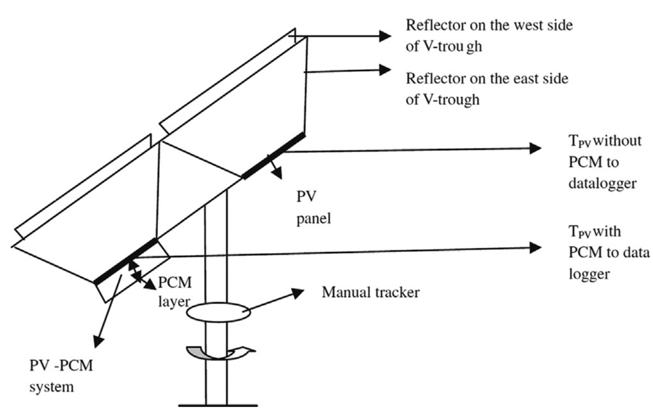

Fig. 35. V-trough stand-alone PV/PCM system [121].

4.3. Heat pipe-based PVT collectors

Heat pipes are considered efficient heat transfer devices that combine the principles of both thermal conductivity and phase transition. A typical heat pipe consists of three sections namely, evaporator, adiabatic, and condenser sections, Fig. 29. Heat pipes provide an ideal solution for heat removal and transmission, with one end serving as a thermal energy collector and the other end as a thermal energy dissipator [51]. Heat pipes have been considered for thermal management applications of PV technology due to the advantages such technology provide over other cooling means such as aiding uniform temperature distribution of PV cells, elimination of freezing that thermosyphon tube can suffer from in higher latitudes, in addition to resistance to corrosion. However, the design of efficient heat pipe involves careful selection of a suitable combination of the heat pipe container material, working fluid, and wick structure [76].

Russell [77] developed a cooling approach for concentrated PV (CPV) systems utilising heat pipes, to enable operation at elevated temperature and utilization of extracted heat for beneficial use. The systems comprised of a row of PV cells mounted on the outer surface of a heat pipe, where heat pipes are arranged next to each other to form a panel, and Fresenl lenses were used to provide high solar energy intensity, Fig. 30. The heat pipe used had internal tubes for circulating a fluid coolant through the heat pipe vapour field to promote heat extraction. Details of the performance parameters were not revealed in this study. Heat pipe approach for CPV system under concentration ratio of about 24 suns was presented by Feldman et al. [78]. The pipe was made out of extruded aluminium surface and the evaporative working fluid was benzene. Under ambient temperature of 40 °C and concentrated solar radiation of 19.2 kW/m^2, a minimum wind speed of 1 m/s was required to keep the evaporator temperature below 140 °C which limits the cooling capability of such system.

Akbarzadeh and Wadowski [79] utilized a passive cooling approach using two heat exchangers piped together and filled

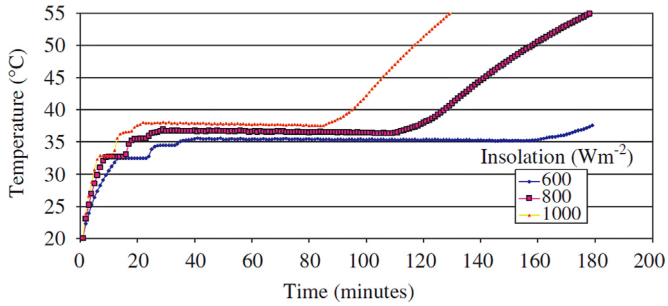

Fig. 36. Surface temperatures at different levels of insolation and ambient temperature of 20 °C [89].

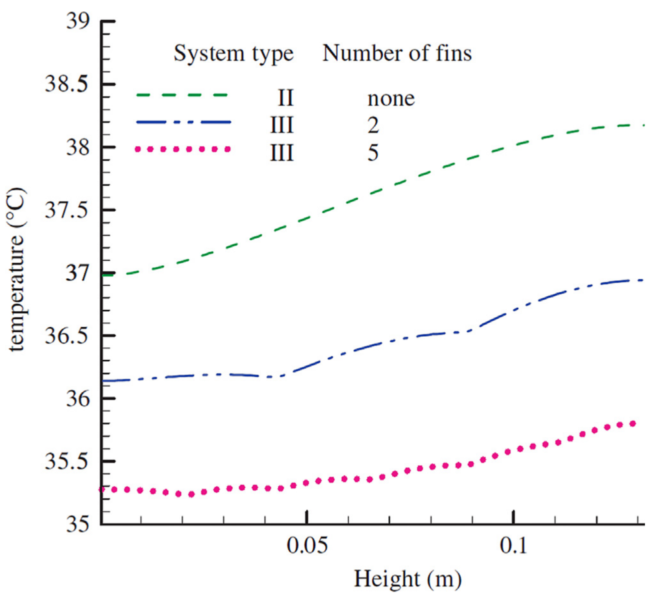

Fig. 37. Surface Temperatures of PV/PCM systems with and without internal fins at a particular operating condition [89].

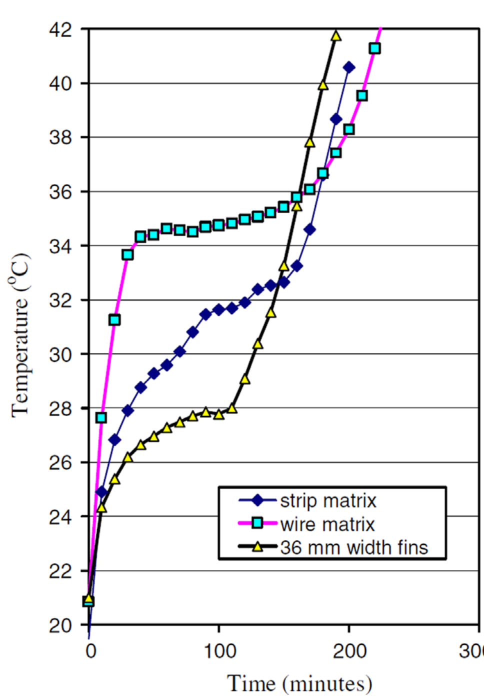

Fig. 38. Average measured surface temperature of finned PV/PCM systems [120].

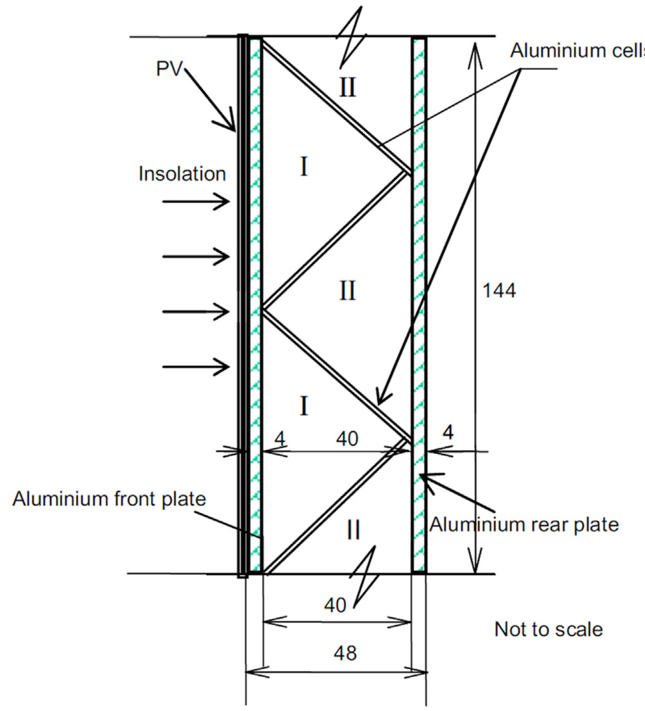

Fig. 39. Schematic diagram of PV/PCM system with triangular cell [94].

with refrigerant to cool the back of the solar cells for a system designed for concentration ratio of 20 suns, Fig. 31. The cooling mechanism proposed has a lower heat exchanger which is an evaporator and flooded with liquid refrigerant, and an upper saturated vapour heat exchanger acting as a condenser. PV cells in this system were attached to the evaporator and the upper condenser was exposed to natural convective air cooling, in addition to fins attached to the condenser to extend the external heat transfer area. Results showed that the solar cell's surface temperature did not exceed 46 °C. Improved performance of 50% was observed, generating 20.6 W compared to 10.6 W for the case without cooling arrangement.

Farahat [80] conducted experimental tests to evaluate the cooling capability of two approaches for concentrator PV cells using water and heat pipe cooling. The study investigated the influence of actual cell temperature on the performance of PV cells by observing the electrical characteristics of PV cells when both cooling techniques were employed. Results showed the influence of temperature on the open circuit voltage which tended to decrease, while the short circuit current increased with the increase in temperature. A comparison of the annual yield of different configurations revealed that decreased temperature of PV cells and a more reliable thermal performance were achieved when heat pipe cooling was applied.

Anderson et al. [81] investigated a design to cool PV concentrator under concentration ratio of 500 suns utilizing a copper/water heat pipe with three wraps of mesh along with aluminium fins to enhance cell cooling with the aid of natural convection. Comparison between different working fluids compatible with copper heat pipes revealed that copper/water heat pipes were able to carry more than six times the power of other working fluids. The heat pipe was fabricated and attached to an aluminium saddle in which the CPV cell sits on, Fig. 32. Optimum fin size and spacing for rejecting heat by natural convection were determined through series of CFD analysis. Heat rejection to the environment through natural convection achieved cell-to-ambient difference of 43 °C when input heat flux of 40 W/cm^2 was applied, whereas temperature difference of 110 °C was measured when aluminium plate was used for PV cells cooling. Adopting the same

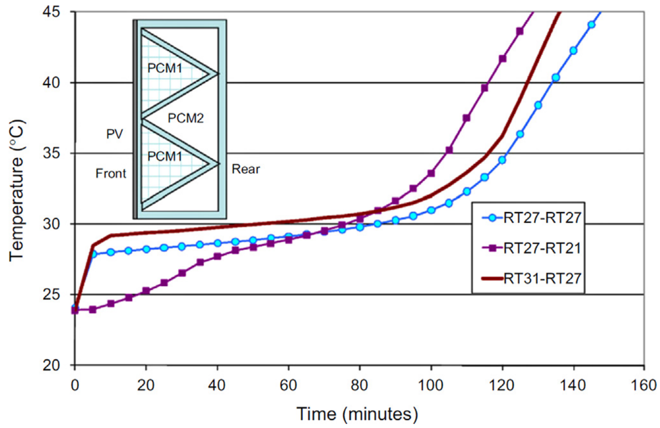

Fig. 40. Predicted surface temperature evolution using different combinations of PCMs within PV/PCM system [94].

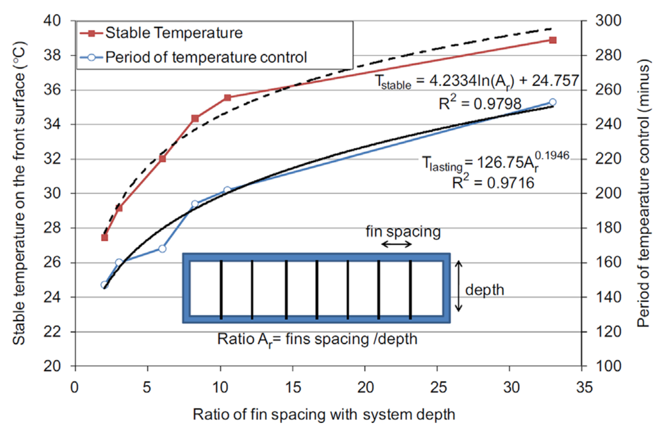

Fig. 41. Temperature regulation with the ratio of fins spacing on PV/PCM system design [123].

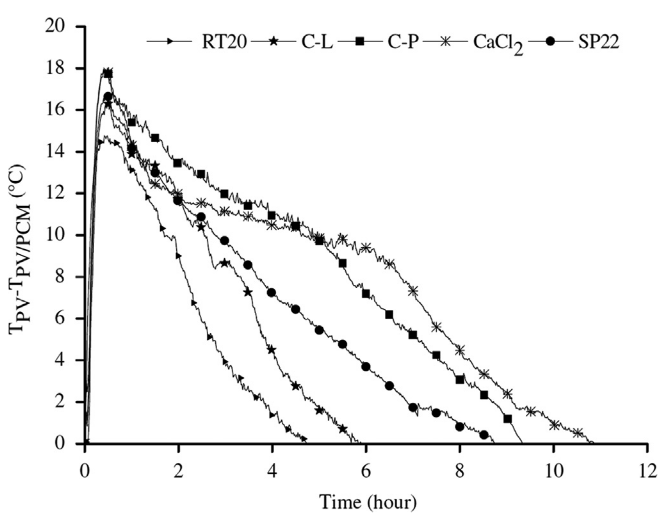

Fig. 42. Temperature difference from reference PV using four different PCMs [118].

concept design, Hughes et al. [82] performed CFD analysis to model the heat transfer from a conventional flat plate PV module. A prototype of the system was fabricated and tested under weather conditions of Dubai, UAE. With the aid of finned heat pipe arrangement and natural convection, the operating temperature of solar cells was regulated at 30 °C under ambient temperature of 42 °C and wind speed of 4.2 m/s.

Tang et al. [83] utilized micro heat pipe arrays to investigate the performance of conventional flat plate PV module using both air and water as heat extraction mediums from the condenser section of the micro heat pipe array, Fig. 33. Experimental results of both systems were compared to an ordinary PV panel without cooling. Using water to cool the heat pipes contributed in achieving a maximum difference in electrical efficiency of 3% and average increase of 0.5%, while air cooling attained 2.6% and 0.4% respectively when compared to ordinary panel without cooling. In terms of output power, the water and air-cooled systems achieved average increase of 9% and 6.3% respectively.

The performance of a water thermpsyphon PVT and a heat pipe PVT collector which was part of a solar assisted heat pump (SAHP-HP) was compared experimentally in Hefei, China in a study conducted by Pei et al. [84]. Heat pipes were used to overcome the freezing issues associated with water thermosyphon PVT collectors in high latitudes and improve the conversion efficiency of PV cells. Heat pipes filled with R600a were utilized and a heat exchanger was incorporated in a water tank (acting as a condenser section of heat pipe), where the working fluid condensed and released its latent heat into the water. The thermal efficiency of the heat pipe PVT collector recorded (23.8%) was 27.9% less than that of the water thermosyphon (33%) attributed to large thermal inertial of the heat pipe PVT system. However, improvement of 6.7% in the electrical efficiency with an average electrical efficiency of 9.5% was achieved through utilizing heat pipe cooling due to small temperature difference between the PV cells compared to that of the water thermosyphon which attained electrical efficiency of 8.9%. The study revealed that utilization of heat pipes in SAHP-HP system has great potential in reducing the power consumption of heat pumps as the heat pipe replaced part of the work of the heat pump.

More recently, Pei et al. [85] conducted dynamic modelling of a PVT collector utilizing heat pipe for heat extraction for PV modules. The collector comprised of 9 water-copper heat pipes joined together at the back of aluminium plate incorporated at the rear of a PV module. Low-iron tempered glass was used as a top cover glass of the installation preventing thermal losses and the entry of dust particles. The model was validated with experimental measurements performed under the weather conditions of Hefei, China, and good agreement was observed. Reported average electrical and thermal energy efficiencies were 10.2% and 45.7% respectively with average overall exergy efficiency of the 7.1%. Pei et al. [85] extended the research to provide a comprehensive parametric analysis based on the validated dynamic model to investigate the effect of water flow rates, PV cell covering factor, tube space of heat pipes, and different solar absorptive coatings of the absorber plate. It was noted that both thermal and electrical efficiencies can be improved by decreasing the inlet water temperature and increasing the mass flow rate. However, the packing factor has an influence on the electrical efficiency greater than that of the thermal efficiency. Cost analysis was also presented in terms of the overall performance improvements that could be achieved by increasing the PV cell covering factor and reducing the tube space of heat pipes. Results of the analysis revealed that heat pipe spacing of 0.09 m was the most suitable and cost efficient option, further reduction in tube spacing resulted in an increased number of heat pipes required for producing a collector at an additional cost with only small improvement in the overall performance. In a similar design Wu et al. [86] investigated the influence of heat pipe cooling on maintaining a uniform cooling for PV cells by absorbing the excessive heat accumulating on solar cells isothermally. Results showed that the use of heat pipe cooling can assist uniform temperature of solar cells on the absorber plate with variation of solar cell temperature less than 2.5 °C. The overall thermal, electrical, and exergy efficiencies of the heat pipe PVT hybrid system reported were 63.65%, 8.45%, and 10.26% respectively.

Redpath et al. [87] investigated the performance of a linear axis compound parabolic concentrating solar PVT (CPC-PVT) with heat

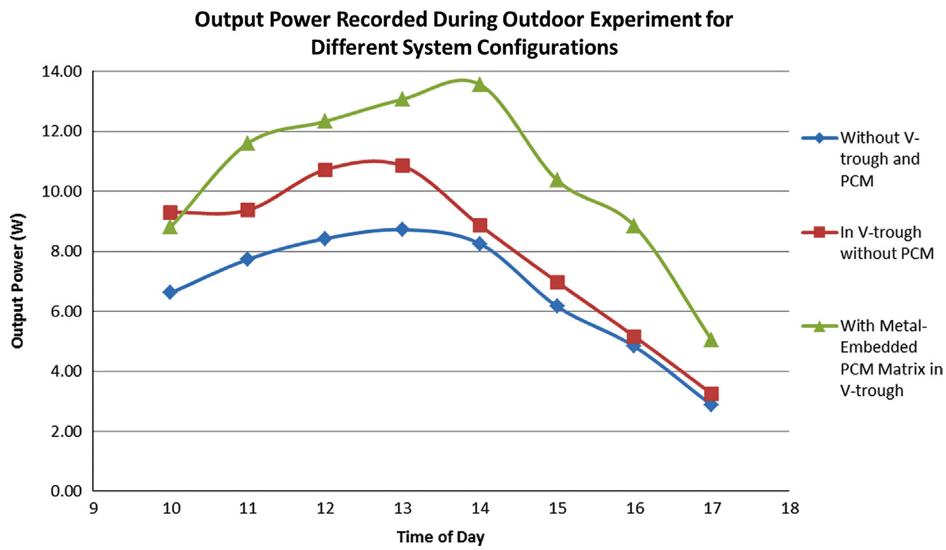

Fig. 43. Output power data of different system configuration taken from [121].

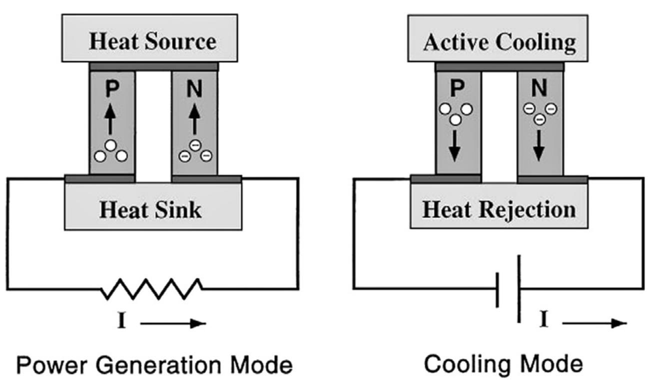

Fig. 44. Operation modes of thermoelectric TE module [131].

pipe integrated for heat removal. The system was compared to a simple flat plate PVT (FP-PVT) with headers and risers. Reported heat loss coefficient of the heat pipe-integrated PVT exhibited lower value than flat plate. Under concentration ratio of 1.8 × the CPC-PVT system attained additional 2.5% in the electrical conversion efficiency, while only 0.9% added efficiency was observed from the FP-PVT comparing both to a reference PV panel. A novel hybrid-structure flat plate heat pipe for a concentrator photovoltaic was fabricated and investigated by Huang et al. [88]. The temperature regulation mechanism comprised of a flat copper pipe with a sintered wick structure, and a coronary-stent-like rhombic copper mesh supports. Such modifications were able to effectively reduce the thermal resistance of the heat pipe allowing for further heat to be extracted. Experimental results with 40 W concentration on the cell achieved improvement of 3.1% in the electrical conversion efficiency compared to an aluminium substrate in a single solar cell.

4.4. PCM-based PVT collectors

Phase changes Materials (PCMs) are substances that are able to absorb and release large amount of energy as latent heat through a reversible isothermal process at a particular phase transition temperature [89–92]. Latent heat storage using PCMs is superior to sensible heat storage due to their higher energy storage density within a smaller temperature range [50]. These materials are classified as organics consisting of paraffin wax, and fatty acids, inorganics consisting of salt hydrates, and eutectic mixtures of organic and inorganic PCMs [93–95]. A thorough review of the three classified PCMs and their desirable characteristics, advantages, disadvantages, and behaviours during phase transition are available in literatures [96–98].

PCMs have been used widely as heat sinks for electronic devices [32,99,100], and in passive thermal storage and management of buildings by adding encapsulated PCM particles during material production processing known as microencapsulated PCMs (MEPCM) or by laminating PCM layers onto construction panels [101–106]. Incorporating PCMs in wallboards, roofs, and ventilation heat exchangers can significantly reduce peak cooling/heating loads leading to reduced energy consumption, in addition to improving human comfort by reducing temperature swings [107–112]. As for electronic devices, incorporating PCMs into traditional heat sinks for electronic chips within mobile phones and computers have been proven effective for thermal regulators [113–115].

As far as PV systems are concerned, conventional passive cooling techniques are unable to provide the required cooling during peak solar radiation periods leading to a deteriorated performance of PVs. Furthermore, inhomogeneous temperature profiles which affect the generation capacity of PV systems stand as a limitation in other passive cooling methods [116,117]. Recently, few studies were conducted to investigate the incorporation of PCMs in PV systems to tackle the aforementioned issues.

Various PCM-based PV concept designs have been reported in literatures. The most common system studied considers incorporation of PCMs in Building Integrated Photovoltaic (BIPV), Fig. 34 [89,118–120]. Stand-alone PV collectors with PCM thermal storage have also been reported in few literatures, Fig. 35 [121,122]. These designs have the same basic components in common from which the system is constructed. However, diversity in the heat transfer mechanisms from the PV module was noted. The unutilized part of solar radiation striking the surface of PCM-based PV systems is conducted as heat to the PCM through the PCM container material causing increased temperature of PCM. At a certain phase transition temperature the PCM starts melting and due to continuous temperature rise the melt extends into the PCM. During latent heat transfer process the PCM effectively acts as a heat sink maintaining a regulated temperature of the PV modules close enough to its melting/freezing point. Once the melting process is complete, any further heat stored will manifest as a temperature rise. Such process is reversible wherein solidification cycle takes place as the temperature drops below the melting point.

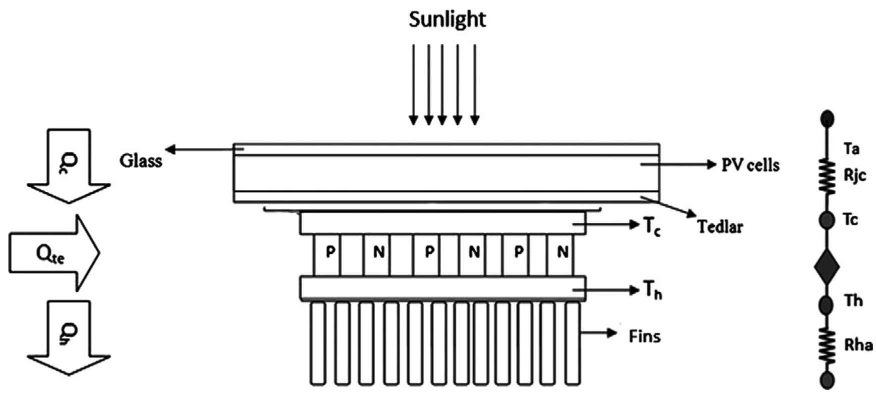

Fig. 45. Cooling of PV cell through TE cooler [142].

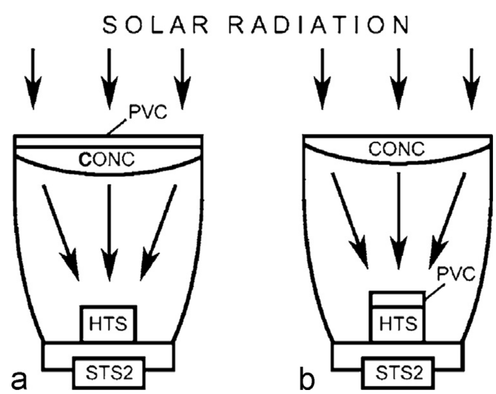

Fig. 46. Incorporation of TE generators with PV cell (a) non-concentrated (b) concentrated [136].

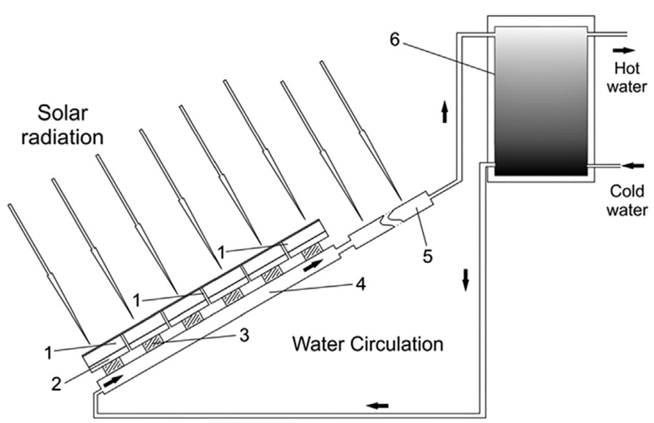

Fig. 47. A scheme of hybrid PV/T system with TEGs: (1) solar cell, (2) cell's back electrode, (3) TEG, (4) heat extractor, (5) plane collector, (6) thermal tank [139].

Non-linear motion of solid–liquid interface, presence of buoyancy driven flows in the melt, and volume expansion of the PCM during melting/solidification introduce complexities in the analytical investigation of PCM-based applications [89]. Therefore, numerical and experimental investigations represent majority of the work reported in this field. Huang et al. [89] developed a two-dimensional model to investigate the use of solid–liquid PCM to regulate the temperature of BIPV near its characterizing temperature of 25 °C. The model was validated with experimental measurements and good agreement was achieved. Parametric analysis based on the validated model was conducted to predict the thermal control of a range of PV/PCM configurations and operating conditions in order to optimize the PV/PCM design. Insolation level had a great influence on the thermal regulation of the PCM in which the time required for PCM to completely melt was reduced as solar intensity increased, Fig. 36. Improvements in the thermal management of the PCM were achieved through incorporating metal fins extending in the PCM as observed in Fig. 37.

Thermal performance of different internal fin arrangements to enhance the thermal conductivity of bulk PCM was investigated experimentally using RT25 and GR40 paraffin waxes by Huang et al. [120]. Of the different fin arrangements investigated straight fins of width 36 mm led to the lowest surface temperature. Soft-iron wire matrix however, sustained stable temperature during phase transition under 750 W/m^2 and ambient temperature of 23 ± 1 °C as shown in Fig. 38. Reported thermal control of solid–liquid RT25 PCM was superior to granular GR40 PCM as a thermal regulation of below 32 °C for a period of 150 min was achieved. Increasing the width of the fin resulted in a longer duration at which the temperature was regulated, while decreasing the spacing between fins further reduced the temperature at the surface of the PV modules at the expense of the temperature control duration. The study concluded that the temperature was mainly influenced by the number, dimension, form of fins, and type of PCM material used.

With regards to the declined thermal regulation period noted through the use of internal fin arrangements, a modified PV/PCM system integrated with two PCMs with different phase transient temperatures was investigated [94]. Various cases using different combinations of PCMs with different melting temperatures in triangular shaped cells were considered, Fig. 39. Compared with the previously studied straight fins PV/PCM, Huang reported that the system with triangular cells was able to dissipate the stress resulting from volume expansion and extended the thermal regulation period. Results of the research revealed that the thermal regulation performance of the PV/PCM depended on the thermal mass of PCM, position of PCMs inside the PV/PCM system, and thermal characteristics of both PCM and PV/PCM system structure. Furthermore, for the combination of PCMs the lower phase transient PCM dominated the whole system performance. Under insolation level of 1000 W/m^2 and ambient temperature of 20 °C the system with PCMs RT27–RT21 had the lowest temperature rise due to its lower melting temperature, while RT27–RT27 was able to regulate the temperature for a longer period, Fig. 40.

The effect of crystalline segregation and convection in melted PCM was also investigated by Huang et al. [123]. The physical structure of bulk PCM in PV/PCM system with phase transition was examined. Increased porosity in the centre of the bulk PCM due to the effect of volume contraction when the PCM solidified was observed, resulting in an increased heat transfer resistance. Although horizontal metal fins enhanced the heat transfer process, obstruction of the movement of bubbles formed under the fins during PCM melting was observed leading to increased heat transfer resistance. Thermal stratification was as well examined

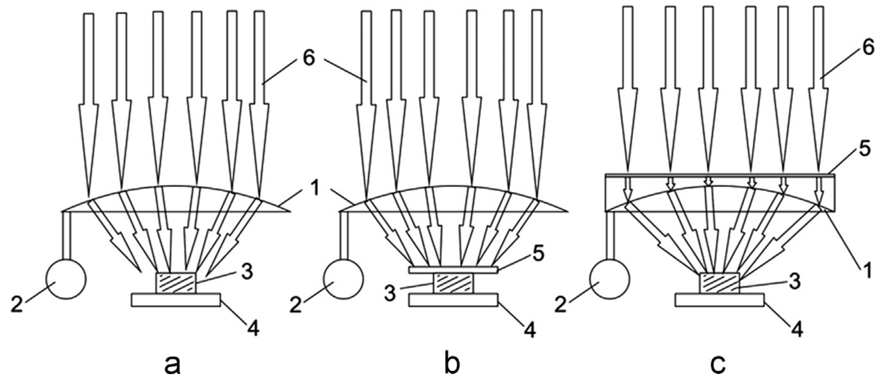

Fig. 48. Scheme of hybrid system with TEG and concentrated solar radiation: (1) concentrating lens, (2) tracking system, (3) TEG, (4) heat extractor, (5) PV panel, (6) solar radiation [139].

through temperature measurements within the PCM, and results showed that with certain fin interval (12–24 mm) the thermal stratification could be reduced and convection had improved effect on heat transfer rate leading to more uniform temperature distribution in the PV/PCM system and improved thermal regulation period. A correlation between the ratio of fins spacing to system depth that can be used to characterize the period of temperature control and temperature regulation capacity is shown in Fig. 41.

Hassan et al. [118] conducted experimental tests and observed the effect of the thermal conductivity of the container material wherein the PCM resides and the effect of thermal mass of PCM on the PV thermal regulation at different insolation levels. Aluminium and Perspex were used as containers attached to the rear of PV module to absorb excessive heat, and various PCMs with different conductivities were examined. Results revealed that salt hydrate $CaCl_2$ PCM in aluminium container achieved the best thermal regulation performance at insolation level of 1000 W/m^2 and ambient temperature of 20 ± 1 °C as shown in Fig. 42. It was evident that the thermal regulation performance of PCMs depended on both the thermal mass of the PCM and the thermal conductivities of both PCM and the overall PV/PCM assembly.

Thermal regulation of an enhanced solar insolation stand-alone PV/PCM system using V-trough was conducted by Maiti et al. [121], Fig. 35. Temperature regulation of 65 °C under 1.7 × average enhancement of solar insolation was attained. The investigated system achieved 55% improvement in the overall power generation through incorporating a bed of metal-embedded paraffin wax as PCM at the rear of the PV module, even under low wind velocities and moderately high insolation and ambient temperature conditions, Fig. 43.

Ho et al. [124] conducted a numerical investigation on MEPCM incorporated in a building structure to realize the thermal and electrical performances of BIPV module under various operating parameters. The significance of PCM melting point choice to match the operating conditions was addressed and proved to be influential on the PCM phase transition cycle completion. In a more recent study, the effectiveness of using a layer of water-saturated MEPCM as a passive thermal management medium for BIPV was explored by Ho et al. [119]. Improvement in average electrical efficiency of 2.006% over the corresponding efficiency for a reference PV module was achieved through integrating a layer MEPCM with a melting point of 30 °C and thickness of 30 mm. PCM with water circulation integrated at the rear of the PV module was examined by Bouzoukas [50]. Among other approaches to cool PV systems PCMs presented fair performance improvements leading to enhanced electrical efficiency and low heat loss coefficient as compared to that of air-, water-, and heat pipe-based systems investigated.

4.5. Thermoelectric (PV-TE) hybrid systems

Thermoelectric (TE) modules are solid-state semiconductor devices that are able to convert thermal energy directly into electrical energy or vice versa. A TE module comprise of thermoelectric elements made of two dissimilar semiconductors, p- and n-type junctions connected electrically in series and thermally in parallel [125]. TE modules possess salient features of being compact, lightweight, noiseless in operation, highly reliable, maintenance free and no moving or complex parts [125–129]. Such devices are categorized into two types of converters depending on the energy conversion process; Thermoelectric Generators (TEGs), generating electricity from a temperature gradient, and Thermoelectric Coolers (TECs), converting a direct current into a temperature gradient [126,130], Fig. 44.

Thermoelectric generators have great potential in waste heat recovery from power plants, automobile vehicles, and solar energy applications where direct heat-to-electricity conversion can occur using a phenomenon called the Seebeck effect [132–135]. For the past 10 years several studies have been conducted to investigate the feasibility of incorporating TEGs with PV technology in a combined cell-scale, flat plate, or even concentrator type systems to harvest energy through thermal waste utilization [136–141]. On the other hand, thermoelectric coolers have been widely used in electronic devices and medical instruments as they are capable of providing refrigeration and temperature control for such devices allowing them to operate at a certain temperature level utilizing the Peltier effect [129,142–144]. In this section a review on the most recent advancements of incorporating of TE modules with PVs to aid lower temperature regulation using TE coolers (TECs) or energy harvesting through direct thermal-to-electricity conversion through TE generators (TEGs) are presented.

TE coolers operate in such way that supplying a low DC voltage to a TEC module enables heat to transfer from one side to the other. Incorporation of TE coolers with PV modules have been studied extensively for refrigeration and temperature management systems, however; these systems are out of the scope of this work. A comprehensive review on PV-driven TEC systems is available in Ref. [144]. Meanwhile, limited research has been done in the application of TE coolers to regulate the temperature of PV cells. The most common design of TE cooler for PV (PV-TEC) systems comprise of TEC module installed at the rear PV cell with aluminium sheet in between so as to spread the heat dissipated at the back surface of the PV cell, Fig. 45 [129,142,143]. In such system, a fraction of the generated power by the PV cell is fed to the TEC module to provide the necessary cooling effect for the PV cell. The cooling effect of a TEC module is characterized by the amount of power supplied, meaning the more electricity is fed into the TEC module the greater the cooling effect for the PV cell. However, there is a trade-off between the net generated power by the system and the power consumed by the TEC module, in which substantial

Table 2
Efficiency of TEG-based concentrator systems for maximum irradiance [139].

System	Concentrator-TEG		PVM-concentrator-TEG	
PV	–	–	a-Si	a-Si
ΔT (K)	150	250	150	250
Concentration ratio	55	95	122	211
$\eta_{0.7}$ (%)	4	6	–	–
$\eta_{2.4}$ (%)	12.4	15.3	15.6	17

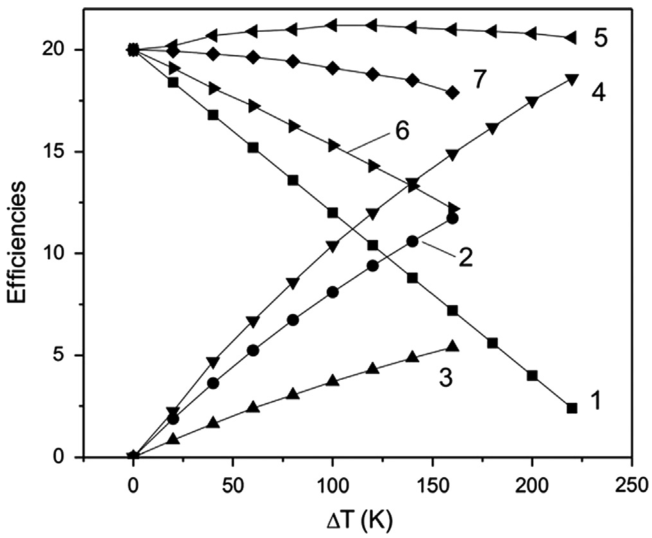

Fig. 49. Calculated temperature dependence efficiency as function the temperature difference: (1) PV cells, TEG with different ZT=2.4 curve (2), 0.7 curve (3), and 4 curve (4), total efficiency with different TEGs (ZT=4 curve (5), 0.7 curve (6), and 2.4 curve (7) [139].

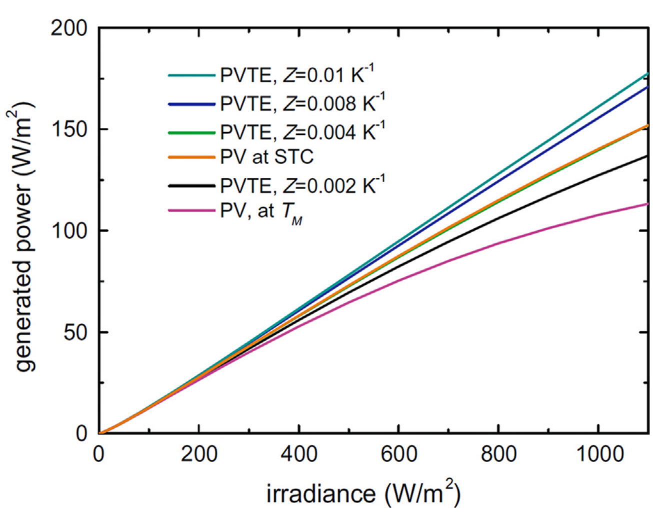

Fig. 50. Generated PVTE power as a function of irradiance for four values of the figure of merit *Z*, and generated PV power as a function of irradiance at STC and module temperature [145].

amount of power is required to achieve significant amount of cooling which can exceed the generated power by PV cells. Therefore, several approaches and control algorithms can be applied by controlling the temperature of the PV cell and keeping it under a specific limit under different conditions or optimization to find the optimal value of the supplied electrical current for the TEC module which leads to the maximum net generated power [142].

Najafi and Woodbury [142] investigated cooling of PV cell utilising the Peltier effect of TEC modules through theoretical model. The system considered a TEC module attached to the back side of a single

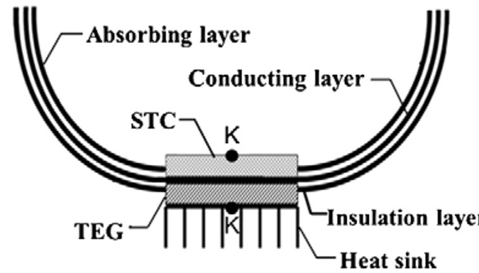

Fig. 51. Schematic of PE-TE hybrid module [146].

Table 3
Performances of TEG, solar cell and hybrid PV-TE module [146].

	FF	V_{oc} (V)		I_{sc} (A)		P_{max} (W)	
		Max	Stable	Max	Stable	Max	Stable
TEG	0.242	3.25	0.86	0.26	0.07	0.204	0.146
Solar cell	0.43	2		0.22		0.189	
Hybrid module	–	–		–		0.393	0.204

PV cell, Fig. 45. The model was used to estimate the temperatures within the system, the required power to supply the thermoelectric cooling module, and the additional power produced by PV cell due to the cooling effect. Evaluation of power saving due to temperature reduction in the PV cell minus the utilized power by the TEC module was estimated through genetic algorithm based optimization in which an optimum value of the supplied electrical current for the TEC module was estimated, which leads to the maximum net generated power at a specific operating conditions. Results revealed that additional power due to cooling was generated, nevertheless, for the optimal current the cooling effect was insignificant and the temperature reduction did not exceed 8 °C. Moreover, it was noted that the performance of the system strongly depended on the figure of merit of the TE module.

Kane et al. [129] utilized TE coolers to aid cooling of PV modules in a building integrated system. A dynamic model of the BIPV/TE system with consideration to PV panel temperature was developed to assess the performances improvement of the TE coolers on PV. The BIPV/TE system comprised of TE module attached at the back of PV module with heat sink attached to the other side of the module to increase heat transfer process. Results revealed that BIPV/TE combined system can be operated at 53 °C PV module temperature without loss of PV power thus module can be cooled down by 10 °C which will enhance life of PV module, and therefore its performance.

Thermoelectric coolers for improved performance of building integrated photovoltaic (BIPV) modules were investigated experimentally by Choi et al. [143]. As control of thermoelectric elements can be regulated independently in an outdoor environment using a micro-controller, the operating temperature of PV cells can be maintained near the characterizing temperature of 25 °C. A control algorithm was built to control the DC current fed into the TE module to achieve the required cooling effect. Comparison between BIPV modules using a ventilator and thermoelectric elements was presented. The TEC was operated when the temperature of the BIPV module exceeds a set temperature, hence operating the BIPV module within the control value only during days with high radiation to achieve additional net power generation. Experimental results showed that average module temperature of 24.48 °C was observed for the BIPV system using a thermoelectric element, while that with ventilator attained average module temperature of 33.31 °C. The output power of the BIPV system was observed to be higher than that with the conventional method and the efficiency of BIPV system was increased.

On the other hand, the incorporation of TE generators with PV cells has been studied extensively to harvest the solar energy available for the sun. In an investigation on the possibility of using TEGs in solar hybrid system done by Vorobiev et al. [136], two different designs were theoretically studied, Fig. 46. To increase the electricity production in PVT the author suggested directing the heat flux originating between the PV module and heat extractor through thermoelectric generator. In the first model the PV cells operated at low temperature, and the thermal solar radiation was concentrated onto the hot side of the high temperature stage (HTS). Therefore, high temperature can be converted to electrical energy through the use of TEGs as the HTS. On the other hand, the second design considered was a system without solar spectrum division, in which PV cells operate at high temperature. The investigation considered two types of PV cell technologies; GaAs single junction cell for model A, and multi-junction GaAs-based cell for model B with corresponding room temperature efficiencies of 24% and 30% respectively under concentration ratio of 50 × . Predicted results showed that model A was able to enhance overall system efficiency by 5–10% while model B with PV cells operating at high temperature did not exhibit much influence on improving the overall conversion efficiency. The investigation however, relayed on theoretical calculation for the investigated models without experimental justifications besides, predictions were given for TEG modules with high figure of merit assumed that are not available in current stage of TEG technology.

Adopting similar design as in [136], an experimental investigation was performed to asses the integration of TEGs in a solar hybrid system in [139]. The model utilized the heat generated under one sun in each PV cell and passed it through individual TEG that have good thermal contact with this cell from one side, and with heat extractor from the other side. The general scheme of the system is shown in Fig. 47, where direct non-concentrated sunlight falls onto the PV panel where each cells possesses a back electrode with high thermal conductivity. The electrodes have direct thermal contact with the hot plate of corresponding TEG. It was noted from the efficiency estimations that with traditional TEGs, one cannot expect significant improvement in electrical efficiency. Due to heat flux losses on the way to TEG, the expected increase of electrical efficiency provided with this TEG model ($ZT=0.7$) was around 1%. Taking the value of ZT equal to 2.4 larger increase due to TEG of 3.2% will be obtained; with $ZT=4$, the efficiency will be 4.1%. Thus the use of existing traditional TEGs in the system studied cannot be really effective, but the advanced TEG might be useful. The authors extended their research to investigate the potentials of achieving better conversion efficiency through concentrated radiation based on three different geometries shown in Fig. 48. From the results obtained it was observed that the conversion efficiency of TEG in concentrated sunlight comparable to that of commercial PV panels can be achieved as presented in Table 2. Although the cost of TEGs currently is slightly higher than that of PV modules of equal surface area, critical reduction can be attained taking into account area reduction of TEG at concentrated irradiation. The second system utilizing concentrated illumination is represented by Fig. 48(b) in which both PV module and TEG work in concentrated irradiation and at elevated temperature, the efficiency of PV decreases with an increase of temperature whereas the TEG's efficiency increases. Therefore, an optimal temperature corresponding to the maximum value of electrical efficiency of the whole device and depending upon the parameters of its components can be identified, Fig. 49. In relation to the hybrid system shown in Fig. 48(c) a transparent a-Si based PV modules with efficiency of 10% and low temperature coefficient compared to c-Si PV modules were used, such modules have the advantage of withstanding high temperature due to the high concentration ratios. The thermal part of the solar spectrum that passes through the cell was determined by the

Table 4
Advantages and disadvantages of different thermal management techniques [118].

	Natural air circulation	Forced air circulation	Liquid cooling	Heat pipes	Thermoelectric cooling	PCM
Advantages	– Passive heat exchange – Low initial cost – No maintenance – Easily integration – Longer life – No Noise – No electricity consumption	– Higher heat transfer rates compared to natural circulation of air – Independent of wind direction and speed – Higher mass flow rates than natural air circulation achieving high heat transfer rates – Higher temperature reduction compared to natural air	– Higher heat transfer rate compared to natural and forced circulation of air – Higher mass flow rates compared to natural and forced circulation of air – Higher thermal conductivity and heat capacity of water compared to air – Higher temperature reduction	– Passive heat exchanger – Efficient heat transfer – Simple – Easy to integrate	– No moving parts – Noise Free – Small size – Easy to integrate – Low maintenance costs – Solid state heat transfer	– Higher heat transfer rates compared to both forced air circulation and forced water circulation – Higher heat absorption due to latent heating – Isothermal natural of heat removal – No electricity consumption – Passive heat exchange – No maintenance cost
Disadvantages	– Low heat transfer rates – Accumulation of dust in inlet grating further reducing heat transfer – Dependent on wind direction and speed – Low thermal conductivity and heat capacity of air	– High initial cost for fans, ducts to handle large mass flow rates – High electrical consumption – Maintenance cost – Noisy system – Difficult to integrate compared to natural air circulation system	– Higher initial cost due to pumps – Higher maintenance cost compared to forced air circulation – Higher electricity consumption compared to forced air circulation – Leakage and pressurization issues	– Expensive – Dust accumulation on the inlet granting – Dependent of wind speed and direction – Dry out – Hot spots – Leakage	– Heat transfer depends on ambient conditions – No heat storage capacity – Require electricity – Requires efficient heat removal from warmer side for effective cooling – Costly for PV cooling	– High PCM cost – Some PCMs are toxic – Some PCMs have fire safety issues – Some PCMs are strongly corrosive – PCMs may have disposal problem after their life cycle is complete

Table 5
Summary of some of the various systems reviewed.

	Work	Configuration	PV type	Electrical efficiency	Thermal efficiency	Overall exergy efficiency	PV cell temperature
Air-based	Dubey et al. [27] (Sim.)	Glass-to-glass PV module with forced air	N/A	10.41% (Annual average)	N/A	N/A	55–75 °C
	Tonui and Tripanagnostopoulos [28] (Sim.)	Unglazed PVT with metal sheet at the middle of the air channel (Natural Convection)	Poly c-Si PV	1–2% Improvement	13%	N/A	3 °C (Reduction compared to regular Air-PVT)
		Glazed PVT with metal sheet at the middle of the air channel (Natural Convection)	Poly c-Si PV	4% Improvement	12%	N/A	4 °C (Reduction compared to regular Air-PVT)
		Unglazed PVT with finned metal sheet at air duct (Natural Convection)	Poly c-Si PV	1–2% improvement	18%	N/A	3 °C (Reduction compared to regular Air-PVT)
		Glazed PVT with finned metal sheet at air duct (Natural Convection)	Poly c-Si PV	10% Improvement	40%	N/A	10 °C (Reduction compared to regular Air-PVT)
	Solanki et al. [29] (Exp.)	PVT air solar heater	Mono c-Si PV	8.40%	42%	N/A	10 °C drop
	Bambrook and Sproul [30] (Exp.)	PVT with open loop single pass duct and extraction fan	Mono c-Si PV	10.6–12.2%	28–55%	N/A	22–28 °C
	Amori, and Al-Najjar [31] (Sim.)	PVT with single pass air duct	Mono c-Si PV	12.3% (Winter), 9% (Summer)	19.4% (Winter), 22.8% (Summer)	N/A	N/A
	Min et al. [39]. (Exp.)	Concentrator PV with metal plates heat sink (400 ×)	MJ-Si PV	N/A	N/A	N/A	37 °C
	Al-Amri and Mallick [40] (Sim.)	Triple-junction solar cell with forced air cooling (100 ×)	MJ-Si PV	N/A	N/A	N/A	150 °C
	Rajoria et al. [43] (Sim.)	Micro-channel PVT tiles, two integrated columns each having 18 PV modules in series are connected in parallel (Case III)	Mono c-Si PV	11.30%	N/A	N/A	N/A
	Rajoria et al. [44] (Sim.)	Micro-channel PVT tiles, two parallel-connected columns of 18 modules each having 36 series-connected PVT tiles to Case III in [41]	Mono c-Si PV	6.5% (Improvement)	18.1% (Improvement)	10.4% (Improvement)	
	Othman et al. [46] (Exp.)	Air-based PVT module with honeycomb heat exchanger	Mono c-Si PV	7.13%	87%		4 °C drop
Water-based	Chow et al. [57] (Exp.)	PVT collector with aluminium-alloy flat-box	Poly c-Si PV	10.3–12.3%	37.6–48.6%	N/A	N/A
	Chow et al. [59] (Sim.)	Vertical wall-mounted water-based PVT	Poly c-Si PV	9.39%	37.50%	N/A	N/A
	Ibrahim et al. [62] (Exp.)	PVT collector with spiral flow design	Poly c-Si PV	11%	64%	N/A	N/A
	Zhu et al. [67] (Exp.)	Dielectric liquid immersion cooling for CPV (250 ×)	Mono c-Si PV	N/A	N/A	N/A	49 °C
Refrigerant-based	Ji et al. [72] (Exp.)	PVT solar-assisted heat pump co-generation with R22 refrigerant	Mono c-Si PV	12%	50%	N/A	N/A
	Zhao et al. [25] (Sim.)	PV/evaporator roof module of heat pump system with R134a refrigerant	Mono c-Si PV	9.21%	60.93%	N/A	N/A
	Zhang et al. [73] (Sim.)	PV/loop-heat-pipe (PV/LHP) heat pump solar system	N/A	10%	40%	N/A	N/A
	Xu et al. [75]	Low concentrating PVT with heat pump (LCPVT-HP) using R134a refrigerant	N/A	17.5 ± 0.4%	N/A	N/A	51 °C
Heat pipe-based	Akbarzadeh and Wadowski [79] (Exp.)	Heat pipe cooling for CPV (20 ×)	N/A	N/A	N/A	N/A	46 °C
	Anderson et al. [81] (Sim)	Heat pipe with aluminium fins cooling for CPV (500 ×)	N/A	N/A	N/A	N/A	43 °C above ambient
	Hughes et al. [82] (Sim.)	Finned heat pipe and natural convection for conventional flat plate PV	N/A	N/A	N/A	N/A	30 °C
	Pei et al. [84] (Exp.)	Heat pipe PVT collector with R600a (part of a solar assisted heat pump)	N/A	9.50%	23.80%	N/A	N/A
	Pei et al. [85] (Sim.)	Heat pipe cooling for flat plate PV	N/A	10.20%	45.70%	7.10%	N/A
	Wu et al. [86] (Sim.)	Heat pipe cooling for flat plate PV	N/A	8.45%	63.65%	10.26%	N/A
	Redpath et al. [87]	Compound parabolic concentrating solar PVT (CPC-PVT) with heat pipe	N/A	2.5% (Addition)	N/A	N/A	N/A
	Huang et al. [88]	flat plate heat pipe for CPV	N/A	3.1% (Improvement)	N/A	N/A	N/A
PCM-based	Huang et al. [89] (Sim.)	Flat plate PV with PCM	N/A	N/A	N/A	N/A	37.5 °C

Table 5 (*continued*)

	Work	Configuration	PV type	Electrical efficiency	Thermal efficiency	Overall exergy efficiency	PV cell temperature
	Huang et al. [123] (Exp.)	Flat plate PV with finned PCM	N/A	N/A	N/A	N/A	27C
	Huang [94] (Sim.)	BIPV with container having two PCM separated in triangles	N/A	N/A	N/A	N/A	28 °C
	Hassan et al. [118] (Exp.)	Flat plate PV with PCM	N/A	N/A	N/A	N/A	18 °C (Reduction)
	Maiti et al. [121] (Exp.)	V-trough metla-wax matrix flat plate PV with PCM (1.7 ×)	N/A	N/A	N/A	N/A	65 °C
	Ho et al. [124]	MEPCM incorporated in a building structure for BIPV	N/A	N/A	N/A	N/A	30.5 °C (Winter), 47 °C (Summer)
	Ho et al. [119] (Sim.)	BIPV integrated with a layer of water-saturated MEPCM	N/A	2% (Improvement)	N/A	N/A	N/A
TE-based	Najafi and Woodbury [142] (Sim.)	PV cell with TE cooler	N/A	N/A	N/A	N/A	8 °C drop
	Kane et al. [129] (Sim.)	BIPV with TE cooler	N/A	N/A	N/A	N/A	53 °C PV (10 °C drop)
	Choi et al. [143] (Exp.)	BIPV with TE cooler	N/A	N/A	N/A	N/A	24.48 °C
	Chávez-Urbiola et al. [139] (Exp.)	PV cell with TE generator	c-Si PV	1% (Addition)	N/A	N/A	N/A
	Sark et al. [145] (Sim.)	Combined PV-TEG	N/A	8–23% (Improvement)	N/A	N/A	N/A

value of band gap, in which for a-Si was 1.6 eV (45% taking into account reflection losses). As per Table 2 the system design (c) can be quite efficient with PV cells made of semiconductor with higher band gap such as CdSe, and using TEG with advanced materials.

Van Sark [145] conducted theoretical investigation on the feasibility and performance enhancements utilizing thermoelectric converters for electricity generation in a PV integrated system. A hybrid module was formed by attaching a series of low temperature thermoelectric converters (i.e. $ZT \geq 1$ at 300 K) to the back side of a PV module to utilize thermal waste available from the PV module. To maintain temperature difference of about 50–60 °C across the TE convertor plates, the converters were mounted on a heat sink to keep the cold plate cooled convectively. The developed model takes into account the influences of irradiance, temperature, and figure of merit on the performance of the PV-TE hybrid module. Results revealed that for the current near-maximum value of $Z = 0.008\ K^{-1}$ additional efficiency of 1.53% was estimated by incorporating thermoelectric converters, while for the current maximum value of $Z = 0.004\ K^{-1}$, PV-TE efficiency of 14.03% was estimated, which resembles the generated power when the PV module was operating at a constant temperature of 25 °C (STC), Fig. 50. The annual performance of the developed system for two cities, namely; Malaga, Spain, and Utrecht, the Netherlands was also evaluated using set of hourly average irradiances and daily ambient temperature and an increase by 14.7% and 11%, for Malaga and Utrecht, respectively was found through the integration of TE converters. Nevertheless, the model ignored the influence of radiation loss through top cover and assumed that the temperature at the hot side of the TE converter equaled the ambient temperature, which may not be realized in practice.

More recently, experimental and theoretical investigation on solar hybrid generation system consisting of 170 mm × 40 mm silicon thin film solar cell, thermoelectric generators, and heat collector was conducted by Deng et al. [146]. The hybrid system developed was in principle similar to the PV-TE hybrid module discussed earlier by Van Sark [145], however, an optimized heat collector design with three layers namely; absorbing, conducting, and insulation layers was introduced to obtain larger temperature difference across the TEG, Fig. 51. The absorbing layer was used to enhance the absorption of sun light, and for that purpose three different types of heat absorbing layer were tested, namely; Graphite, optical–thermal thin film, and black polymer tape. A bowl-shaped copper foil was fabricated and fixed to the side and back of the solar cell to accelerate heat conduction to the TEG, while a layer of foam was applied to prevent heat loss. To enhance heat dissipation and maintain larger temperature difference across the TEG plates, both aluminium fin heat sinks attached at the cold side of converter and water cooling was investigated. To assess the performance of the TEG in the hybrid system the open circuit voltages and short circuit currents for the design with black polymer tape as an absorbing layer and aluminium fins to cool the TEG were recorded in Table 3. Results showed that the integrated design had an enhanced overall performance. The numerical simulation performed on TEG estimated increased heat flux on the hot side of the converter by more than tenfold using the optimized thermal collector design.

5. Discussion

Various methods can be employed to achieve cooling action for PV systems. However, the optimum cooling solution is critically dependent on several factors such as, system arrangement, PV technology employed, types of concentrators' geometries, and weather condition at which the system is installed. Hybrid PV System offer a practical solution to increase the electrical power production from PV panels and reduce the heating loads, in addition to the recovery of heat extracted from the panels. Heat extraction from PV modules utilizing various mechanisms was presented. Various designs employing air, liquid, heat pipe, PCM, and thermoelectric modules to aid cooling of PV cells were discussed along with the parameters influencing the system performance.

Air cooling of PV system provides a simple technique to thermally regulate the temperature of PV cells owing to minimal use of material and low operating cost among other PV cooling technologies. Forced air enhances heat extraction resulting in further improved performance of air PVT systems when compared with naturally ventilated ones at the expense of some parasitic power losses introduced due to the use of air blowers. Nevertheless, the low density and small heat capacity of air, limits the improvements in the performance of air PVT collectors making air less favourable option. On the other hand, liquid cooling offers a better alternative to air cooling utilising coolant allowing a more efficient utilization of thermal energy captured. In addition, liquid-based PVT collectors offer less temperature fluctuations compared to air-based PVT making them more favourable in aiding a

homogenous temperature distribution on the surface of PV modules. Water is the most common fluid employed in liquid-based cooling of PV systems; however, refrigerants that are able to undergo phase change at a relatively low temperature have been practically investigated and offered better performance. The use of heat pipe cooling of PV cells aids a uniform temperature distribution of PV cells in addition to elimination of freezing that thermosyphon tube used in water-based cooling. PCMs however, offer both high heat transfer rates and heat absorption due to latent heating, which make them attractive for PV cells cooling application. The incorporation of thermoelectric devices with PV systems seems very attractive when operating at generation mode, however, the supplemental energy generated by the thermoelectric device requires large temperature difference across the hot and cold plates of the device, making improvement in performance limited with the current technologies available. List of advantages and disadvantages of each of the cooling technologies for PV cells discussed earlier are given in Table 4. A summary of some of the various systems that have been reviewed is provided in Table 5.

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